A Systematic Literature Review Assessing Nearshore Closed Containment Systems for Salmon Farming in British Columbia

Prepared by

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A project report submitted in partial fulfillment of the requirements for the degree of

BACHELOR OF TECHNOLOGY IN ENVIRONMENTAL ENGINEERING in the

SCHOOL OF CONSTRUCTION AND THE ENVIRONMENT

(Environmental Engineering)

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December 17, 2022

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Abstract

To assess the ways in which marine closed containment systems (CCS) for salmon farming may be a sustainably viable option in replacing open net pen systems (ONPS) currently used in British Columbia, I undertook a systematic review of literature on the subject.

The literature search for this review was conducted by examining online databases and primarily focused on more recently published literature (between 2000 and 2022), and the information sources were selected based on their topic relevancy and quality. The selected sources included primary research, reviews, assessment reports, and grey literature on nearshore marine closed containment salmon aquaculture. Finally, the gathered material was discussed based on the environmental, economic, and social impacts of marine CCS versus ONPS.

The results from this systematic literature review suggest that the type of pen operations and infrastructure used by CCS could change the level of impacts and costs associated with this technology in marine environments in a positive way. Thus, marine CCS may be a viable option in replacing ONPS for salmon farming in British Columbia due to the following reasons:

1. they are likely to have lower environmental impacts such as lower sea lice and disease transmission to wild salmon, less waste loading to the surrounding aquatic environment, and lower risk of fish escapes;
2. they may contribute more to Canada's gross domestic product due to increased production from the capability to stock higher densities of salmon in a CCS pen;
3. they can help keep most ONPS jobs that are currently in place if a phase-out of ONPS were to occur; and
4. they may provide opportunities for jobs with increased salaries compared to ONPS.

The type of pen operations and infrastructure used by CCS could change the level of impacts and costs associated with this technology in marine environments. Thus, the siting of marine CCS should consider hydroelectric grid connectivity so that the dependence on fossil fuels is decreased as much as possible. This will better ensure that the life cycle environmental impacts associated with marine CCS may be kept lower than that of ONPS. Furthermore, to better represent the impacts and risks of a specific CCS farm more accurately, it is recommended that additional research be done on how variables such as conditions within the pen, structural integrity and effluent dispersal may change at the intended farm location.

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List of Acronyms

ACD – acidification
CED – cumulative energy demand
CCS – closed containment system
DFO – Department of Fisheries and Oceans (Canada)
EPA – United States Environmental Protection Agency
EUT – eutrophication
FAO – Food and Agriculture Organization of the United Nations
GWP – global warming potential
HTP – human toxicity potential
ILAB – The Industrial Laboratory (Norway)
IMTA – Integrated multi-trophic aquaculture
LCA – lifecycle assessment
MTP – marine toxicity potential
NOAA – National Oceanic and Atmospheric Administration of the United States
ONPS – open net pens systems
OWI – operational welfare indicator
PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RAS – recirculating aquaculture systems
SSAT – State of Salmon Aquaculture Technologies
SWF – mass-specific water flow
TAN – total ammonia nitrogen
UV – ultraviolet

List of Symbols and Selected Units

BL/s – a unit of speed for a moving organism with its units in "body lengths", e.g., salmon body length per second.
kg/m^3 – a unit of density, e.g., kilogram of fish per cubic meter of farm space.
$L\ kg\ fish^{-1}\ min^{-1}$ – a unit of mass flow rate, e.g., flow of water in litres per kilogram of fish per minute.
mg/L – a unit of concentration, e.g., milligram per litre of CO2 or NH3.
mJ/cm^2 – a unit of irradiance, e.g., the amount of ultraviolet radiant power hitting a square centimeter of passing water (Stowe, 1999).
ug/L NH_3-N – a unit of concentration, e.g., micrograms of ammoniacal nitrogen per litre of water.

Glossary

Biofouling

An accumulation of waterborne microorganisms on structures that are in water (*Definition of BIOFOULING*, n.d.).

Broodstock

Reproductively mature animals that can be used to establish new populations (*Broodstock*, n.d.).

Circular economy

An economy in which "products are made to last longer, communities share resources and save money, and businesses are maintaining, reusing, remanufacturing and recycling materials to create more value" (*Circular Economy*, 2022)

Crustaceans

Invertebrate animals, of the subphylum Crustacea, that typically live in aquatic environments such as crabs, lobsters, and shrimps (Gordon and Green, 2022).

Fillet gaping

When a fish is filleted and slits and/or holes appear in the flesh as opposed to it being smooth and glossy (Loye, n.d.)

Gross domestic product

The total value of all the goods produced and services provided by a country within a period of time (*What is gross domestic product*, n.d.).

Integrated multi-trophic aquaculture

An aquaculture process where productions are set up so that wastes generated by one species can by utilized by another species. (*Integrate Multi-Trophic Aquaculture*, 2022)

Lifecycle assessment

An "analysis technique to assess environmental impacts associated with all the stages of a product's life" such as raw material extraction, manufacturing, distribution, use, and end of life disposal (Muralikrishna and Manickam, 2017).

Mass-specific water flow

The "mass of fluid passing a point in [a] system per unit time" (*Mass Flow Rate Fluids Flow Equation*, n.d.).

Nephrocalcinosis

A known production-related disease in salmon aquaculture; it is caused by "the accumulation of calcium and magnesium deposits in the kidneys" and negatively impacts the welfare of salmon within the farm (Klykken et al., 2021). One possible reason for its cause among farmed salmon is exposure to high concentrations of CO_2 when water quality in the farm is diminished (Klykken et al., 2021).

Recirculating aquaculture systems

Aquaculture systems that have components in place that allow for water to be filtered and recirculated (*Explained: What is RAS Aquaculture?*, 2021).

Sea lice

Crustacean parasites of the subclass Copepoda that feed on the external skin and mucus layers of salmon (Frazer, 2009).

Turbidity

A measure of the relative clarity of a liquid based on how much light scattering occurs as a light is shone through the liquid (*Turbidity and Water*,2018). The increasing presence of particles such as silt, microorganisms, organic matter, and dissolved coloured organic compounds makes the liquid increasingly turbid (*Turbidity and Water*, 2018).

Acknowledgments

Firstly, I would like to thank my advisor, Dr. Marvin Rosenau who helped me immensely throughout the proposal and project writing process by answering all my questions, reviewing and providing suggestions on my material, and sharing resources to further my knowledge on the subject matter. I am very much appreciative of the time and effort he took in helping me with this project.

I thank Dr. Olga Petrov for her feedback and suggestions throughout the preparation of this project. I also thank Laurie Izgerean for her feedback on my writing and for answering all my queries regarding referencing.

I would also like to thank Dr. Zahra Tooyserkani and Fiona Lemon for their help and advice throughout the proposal writing process.

Chapter 1: Introduction

1.1 Background

1.1.1 An Overview of Aquaculture

Food scarcity, resource depletion, and the overall ability of our planet to provide for the needs of future generations have become a growing concern as human population has been rapidly increasing over the last two centuries (Food and Agriculture Organization of the United Nations [FAO], 2021). With terrestrial farming starting to reach its footprint limits for production, new innovations and developments in the field of aquaculture technology have been taking place in the food production industry to better meet the nutritional demands of our growing human population. The term "aquaculture" refers to the "breeding, rearing, and harvesting" of organisms in an aquatic environment, inclusive of both freshwater and saltwater environments (*What is aquaculture?,* 2016).

Atlantic Salmon (*Salmo salar*) is among the top 10 species groups in global aquaculture as reported by the FAO (Cai et al., 2017). Canadian farmed salmon accounts for 8% of the global production of this taxonomic group, making Canada the fourth largest farmed salmon producer in the world (Department of Fisheries and Oceans [DFO], 2012). Among the Canadian provinces, British Columbia is the largest contributor to the nation's salmon aquaculture production, accounting for over 75% (by weight) of the total production in 2020 (Statistics Canada, 2021). Most of this production occurs in the nearshore marine environment facilities known as open net pens systems (ONPS) (State of Salmon Aquaculture Technologies [SSAT], 2019)

1.1.2 Salmon Farming in British Columbia

Salmon farming in marine environments began in British Columbia in the early 1970s with the culture of some of the local Pacific species, including Chinook (*Oncorhynchus tshawytscha*) and Coho (*O. kisutch*) salmon (Environment Assessment Office [EAO], 1997). However, Atlantic Salmon soon became the dominant cultured salmonid in this province due to their more favourable commercial production aspects. This included characteristics such as "faster growth rate[s] [than Pacific Salmon] and greater tolerance[s] for higher stocking densities" (EAO, 1997).

During the expanding phase of this industry, in British Columba, the "grow-out" stage of Atlantic Salmon production mainly took place in protected waters of the marine environment in flow-through net pens. This largely started in the Sunshine Coast region, before expanding to other areas such as the Discovery Islands, the east and west coasts of Vancouver Island, and the

Broughton Archipelago (Cohen, 2012). This industry expanded dramatically from 1995 onwards and plateaued throughout the years 2015-2020 and farmed Atlantic Salmon is now ranked as the number one agriculture and seafood export in British Columbia (AgriService BC, 2022). As an example of its value, in 2020, British Columbia produced 100, 269 tonnes of Atlantic Salmon which was valued at CAD 665 million (Statistics Canada, 2021).

The culture of farmed salmon is important to the economy and social fabric of British Columbia. Not only does salmon aquaculture add monetary value to British Columbia's industrial output, but it also has positive socio-economic impacts through the provision of direct jobs within the industry and indirect jobs in areas such as transportation and supply of goods and services (DFO, 2010). In 2010, it was reported that the aquaculture industry in British Columbia provided 6,000 full-time equivalent job positions (DFO, 2010). Moreover, the societal benefits are considered by some to be significant. For example, according to the Aboriginal Aquaculture Association, people of indigenous descent make up approximately 14% of British Columbia's aquaculture labour force (Cohen, 2012). Furthermore, due to the location constraints of salmon farms, related jobs exist mostly in isolated coastal communities where job opportunities are typically limited (DFO, 2010). Thus, aquaculture has aided in the socio-economic growth of smaller communities such as those in the Campbell River and Comox-Strathcona regions (DFO, 2010).

1.1.3 Salmon Farming Process

Salmon farming has several stages that connect to form a production cycle as shown in Figure 1. The initial stages of salmon farming take place in freshwater hatcheries where brood-stock selection, egg stripping and fertilization, and hatching and incubation of embryos and alevins occur. After emergence, the fry are transferred to freshwater tanks where they are reared to a size and stage until they become salt-water tolerant. Freshwater rearing of smolt occurs until they weigh 75-100g (*Cultured Aquatic Species—Salmo salar*, 2004; DFO, 2010). Next, the post-smolt stage growth takes place in seawater net pens where the juvenile salmon are grown out to market sizes that are upwards of 2kg (*Cultured Aquatic Species—Salmo salar*, 2004).

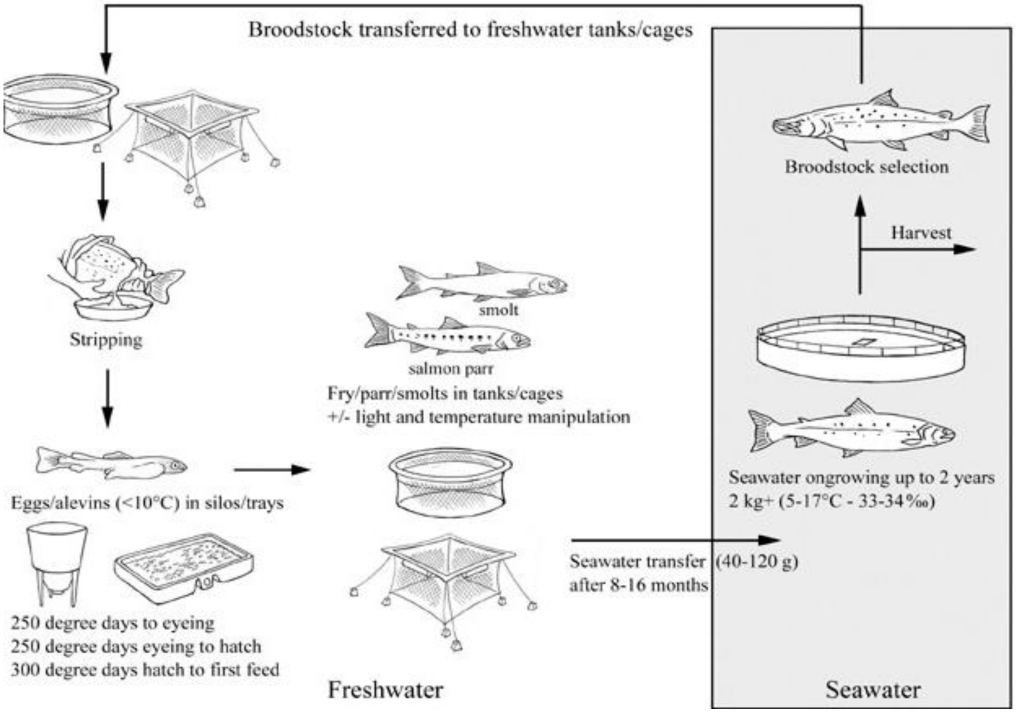

Figure 1. *Marine-based aquaculture production cycle of Atlantic Salmon (Salmo salar) where grow-out occurs in saltwater open net pen systems (Cultured Aquatic Species—Salmo salar, 2004).*

1.1.4 The Negative Impacts of ONPS Salmon Aquaculture in British Columbia

Although salmon aquaculture contributes to economic growth and the development of remote communities in British Columbia (DFO, 2010), some people within the scientific community, First Nations, and the general public have a negative outlook on ONPS salmon farming due to the perceived environmental risks associated with this technology (Froehlich et al., 2017).

The Cohen Commission Report (2012) indicated that one of the most voiced concerns regarding ONPS salmon farms was their potential effect on wild salmon populations. Figure 2 displays the Sockeye returns in the Fraser River during 1989-2021 as 4-year running averages and British Columbia's annual farmed fish production during 1991-2021. Soon after commercial farmed salmon productions began in British Columbia several decades ago, the Sockeye Salmon returns were seen to drop precipitously, while farmed fish productions had an overall upwards trajectory (Figure 2). This pattern is consistent for many Georgia Straight/Salish Sea and Fraser River populations of anadromous salmonids (Rosenau, 2022). Thus, there is an apparent correlation, between declining wild fish numbers, and fish farm increases in production for some parts of British Columbia where juvenile salmonids migrate through dense fish-farming areas (Figures 2 and 3). But more research needs to be undertaken in these regards.

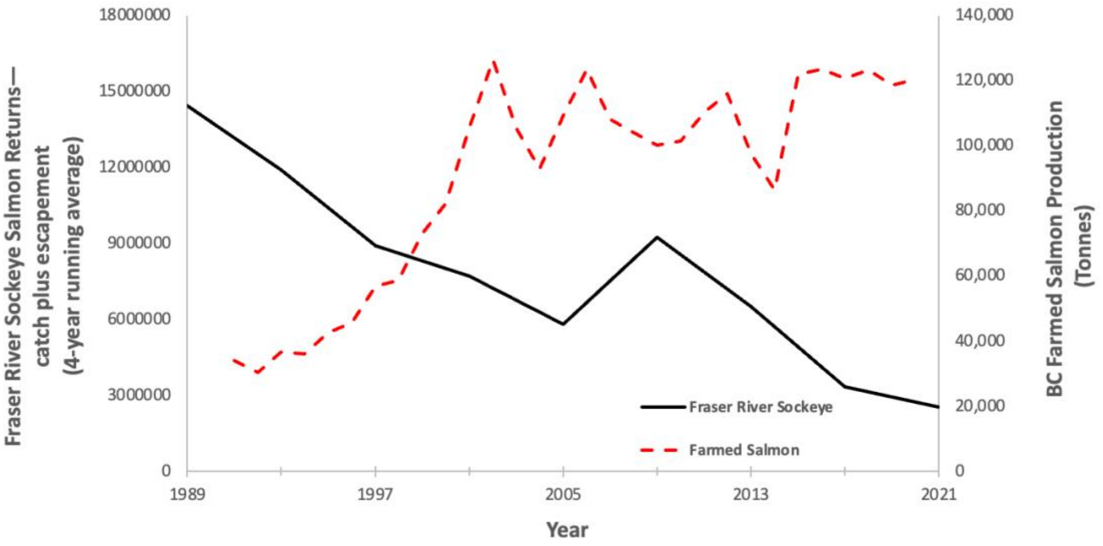

Figure 2. *Fraser River sockeye salmon returns compared to BC farmed fish production from 1989-2021 (Rosenau, 2022).*

Most grow-out pens in British Columbia are located in marine-coastal waters, and normally in protected bays, channels, or inlets where waters tend to have shallow, low-velocity current characteristics (SSAT, 2019). These waterways are all salmon smolt migration routes and are usually comprised of highly productive marine littoral feeding areas. Notably, the weaker currents used by the facilities for flushing flows for the ONPS in these regions may increase the chance of waste and contaminant build-up occurring in the vicinity of the ONPS, including the benthic environments, compared to the adjacent main channels (SSAT, 2019).

A related topic examined by the Cohen Commission (2012) was the proximity of ONPS salmon farms to wild and hatchery juvenile salmonid migration routes and the potential for deleterious effects of these facilities on these young fish. The impacts relating to disease and parasitism (e.g., sea lice) have long been of most interest to many people (Cohen, 2012).

In 2016, many of the Greater Georgia Basin salmon farm locations in British Columbia (shown as yellow circles in Figure 3) overlapped with the major wild and hatchery juvenile salmon migration routes (shown as red lines with arrows in Figure 3), especially those emanating from the Fraser River watershed and natal streams flowing into the Salish Sea and Puget Sound. In these overlapping regions, there are many correlations of population collapses in wild salmonids travelling through areas of ONPS, and over the timing of the increase in farmed production (Environmental Protection Agency [EPA], 2013).

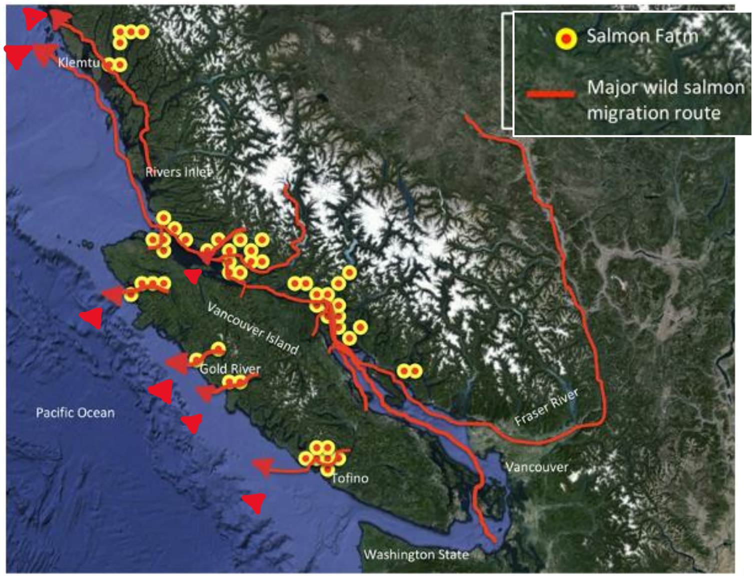

Figure 3. *Location of fish farms and major wild salmon migration routes in southern British Columbia marine waters (Where they operate, 2016).*

Other parts of British Columbia (e.g., the west coast of Vancouver Island) have also had an influx of fish farms and apparently synchronous collapses in wild and hatchery production of salmonids migrating through their footprint areas (Cohen, 2012). These observations indicate that it is especially important, to consider any deleterious impacts the salmon farms may be causing to these waters if they are to be considered sustainable in British Columbia.

As shown in Figure 4, below, OPNS infrastructure used during salmon grow-out is comprised of seabed-anchored metal mesh cages that float in the water and are open to the surrounding aquatic environment (DFO, 2010).

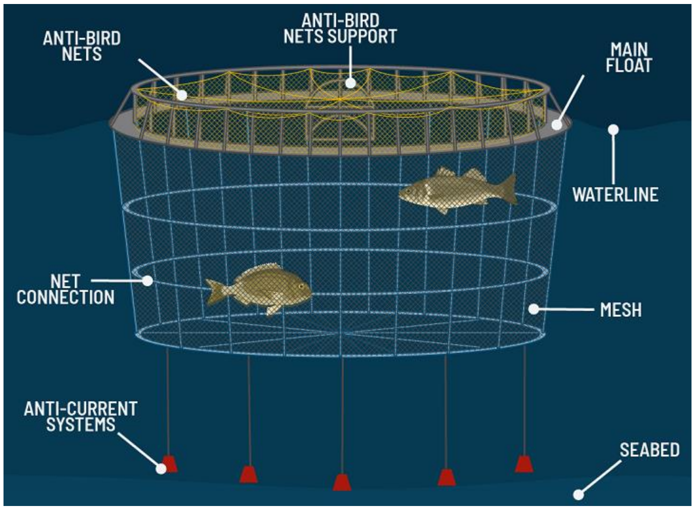

Figure 4. *Schematic of an open net pen system (OPNS) salmon farming cage infrastructure (Derwent Group, n.d.)*

The sub-surface mesh openings of the ONPS (Figure 4) allow for seawater to freely flow through the cage and for uneaten feed, fish waste, CO_2, and any other potentially deleterious additions to the pen (e.g., excess pesticides, herbicides, etc.) to flow out into the nearby ambient environment as well. The implicit basis of this industry is that soluble wastes are expected to disperse into the ocean with the help of currents, while the solid wastes fall and settle onto the seabed and are assimilated by the local benthic ecosystem (Boulet et. al., 2010).

Many studies (e.g., Hutchings et al., 2012; Liu et al., 2011; Morton et al., 2017) indicate that salmon farming using open net pen systems (ONPS) may result in significant changes to the nearby aquatic environment, causing harm to coastal ecosystems and migrating juvenile salmon. This is because the interior of the ONPS is connected to the surrounding environment which allows for the uncontrolled mass transfer of deleterious substances to occur between the net pen and the ambient open water. Some of the more contentious environmental issues thought to be associated with OPNS salmon farming include pathogen and parasite transfers (Cohen, 2012; Frazer, 2009), the release of pesticides and herbicides (Haya, 2001), farmed salmon escapes (SSAT, 2019), and organic waste release (Hall-Spencer and Bamber, 2007).

The transfer of bacterial and viral pathogens and parasites from farmed salmon to migrating juvenile wild salmon is of significant concern in British Columbia (Cohen, 2012). Bacterial and viral diseases, such as infectious salmon anemia virus (ISAv) and *Piscine orthoreovirus* (PRV) are known to occur in ONPS salmon farms in British Columbia and may be transferred to the ambient fish environment (Cohen, 2012; Morton et al., 2017). Sea lice (*Lepeophtheirus salmonis* and *Caligus* elongatus), which are copepod parasites that feed on the external skin and mucus layers of salmon, are also a common issue with ONPS salmon farming (Frazer, 2009). Sea lice are detrimental, particularly to juvenile salmon, as they disrupt their host's osmotic system, cause skin wounds and lesions that weaken the fitness of their host, and these open wounds also allow for bacterial and viral infections to transmit more easily (Frazer, 2009). In their weakened state the juvenile salmon are almost certainly more susceptible to predation. Although most of these diseases and parasites are naturally occurring within the aquatic environment, the issue is more prevalent when fish farms are stocked at high densities and located in regions with low currents, increasing infection rates within the pen, and thus, to the fish in the outside waters (Frazer, 2009). That is, ONPS are potentially zones of biomagnification of deleterious biotic infestations to the adjacent environments.

Due to the salmon farms' proximity to major wild salmon migratory routes where the young travelling salmonids are in high concentrations (Cohen, 2012), infestations of high-density diseases, contained within the open net pens, could lead to increased infestations of wild and hatchery juvenile salmon passing by the net pens (Frazer, 2009; SSAT, 2019). Such pathogens and parasites could negatively impact the survival rates of these migrating juvenile smolts, potentially exacerbating the population declines of native salmon (Cohen, 2012).

The Cohen Commission Report (2012) suggested that wastes and chemicals discharged from salmon farms were not likely to impact the population of wild salmon. However, looking at the issues from a broader ecosystem perspective, there is evidence that suggests that these releases can cause significant negative impacts on the benthic environment under open pen farms. A study by Hall-Spencer and Bamber (2007) observed the effects of wastes from a salmon farm in Shetland, UK, that had been located above a maerl (type of seaweed) bed since 1991. Results from this study indicated that organic matter and chemicals released from the farms caused combined negative effects on benthic crustacea including reductions in population numbers and species diversity. These results are complementary to research conducted by Haya (2001) which sought to determine the environmental impact of chemical waste from ONPS salmon aquaculture in the Bay of Fundy, Nova Scotia. Through laboratory studies, Haya (2001) found that some of these wastes posed a biological risk to native organisms in the surrounding waters, particularly crustaceans. Analysis of chemicals used in sea-lice treatments such as SLICE® showed that they negatively impacted the reproduction of lobsters at sub-lethal levels. As crustaceans play an important role in nutrient recycling and are also part of the aquatic food web (*Crustaceans: Natural science*, 2022), the negative impacts on these organisms by ONPS wastes suggests that releasing these deleterious materials without treatment may pose a hazard to the local ecosystem.

Knowing that there is a potential to cause adverse effects on aquatic organisms due to waste release, aquaculture organizations wanting to adopt sustainable practices will need to investigate how effluent must be properly treated. Hence, at its most basic, to collect outflowing pen-water for treatment, the ONPS would need to entrain it to a concentrated location within the facility in a way that it could be properly treated. Thus, for this to be realistically achieved, there is the need for some sort of closed-pen containment aquaculture system and amelioration of salmon farming wastewater before it is released into the outside environment.

With respect to farmed salmon escapees and their likely impact on wild salmon, the Cohen Commission Report (2012) indicated that the evidence reviewed showed that cultured fish leaving the pens did not have a known significant negative impact at the population level in British Columbian wild salmon. This primarily pertains to impacts related to competition for spawning habitat and food. Yet, Cohen (2012) and SSAT (2019) still view farmed salmon escapees as an environmental issue that still needed to be considered since large numbers of farmed fish escapees could potentially offset the natural equilibrium of certain British Columbia salmonid ecosystems.

1.1.5 Mitigating the Environmental Impacts of Salmon Aquaculture

The environmental issues regarding ONPS of the British Columbian salmon farming industry are linked to a common factor which is the open-water flow between net pens and their aquatic surroundings. With no control over what is entrained in the water flowing out of these pens, interactions between the two sides of the nets could lead to harmful effects on the external aquatic environment (DFO, 2009). Due to concerns expressed by the environmental community over the last several decades, particularly about the declining wild salmon stocks in the southern part of British Columbia since the 1990s, the Federal Government of Canada has mandated a phase-out for British Columbia’s coastal open net pens by 2025 (DFO, 2022). This move to remove ONPS in British Columbia marine waters was initiated in 2018 for open net pen salmon farms in the Broughton Archipelago and then, more recently, in 2019 for net pen salmon farms in the Discovery Passage region (DFO, 2020). This is consistent with some components of senior governments encouraging a transition to more contained systems that decrease interactions between the farming pen and the surrounding aquatic environments (DFO, 2021).

1.1.6 Marine Closed-Containment Salmon Aquaculture Systems

In the hopes of addressing the environmental issues regarding ONPS and reducing the deleterious impacts of aquaculture, new finfish farming technologies with barriers between the interior of the marine grow-out pens and the aquatic environment are being studied (Boulet et al., 2010). The *Feasibility Study of Closed-Containment Options for the British Columbia Aquaculture Industry*, prepared by Boulet et al. (2010) for the DFO, reviewed four aquaculture technologies: conventional open net pen (ONPS), marine closed containment with rigid walls, marine closed containment with flexible walls, and land-based technologies (i.e., conventional fish hatcheries located on dry land and similar to that often seen operated by DFO and the Freshwater Fisheries Society of British Columbia [FFSBC]). The basics of marine CCS and land-based CCS are further discussed in this subsection.

Closed containment systems (CCS), with either rigid or flexible walls, are both categorized as marine CCS and are sometimes referred to as semi-closed containment systems (S-CCS) (SSAT, 2019). The flexible-walled structures are typically water-impermeable bags made of heavy-gauge polyvinyl chloride (Figure 5), while the rigid-walled structures are reminiscent of tanks (Figure 6) (Boulet et al., 2010).

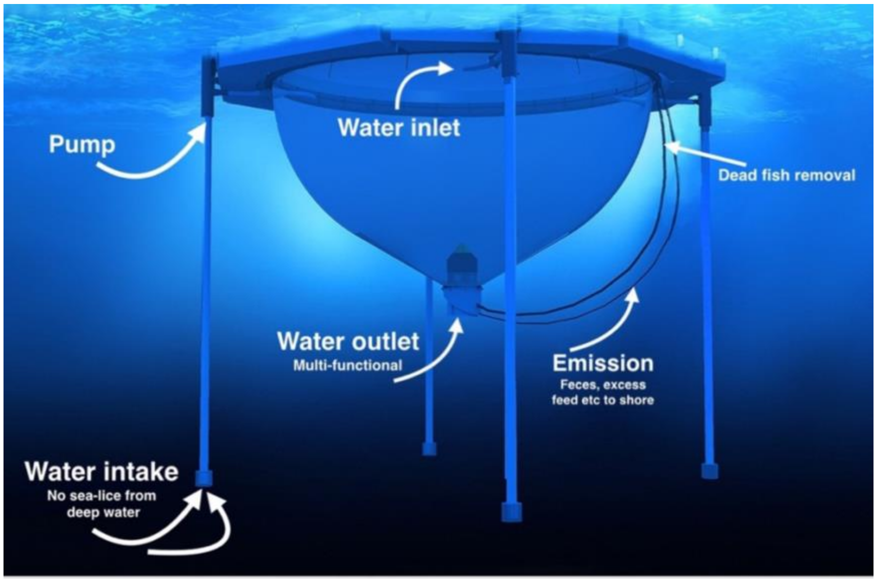

Figure 5. *Schematic of a flexible-walled CCS where the effluent is separated into three streams: water, sludge, and dead fish (Nilsen et al. 2020).*

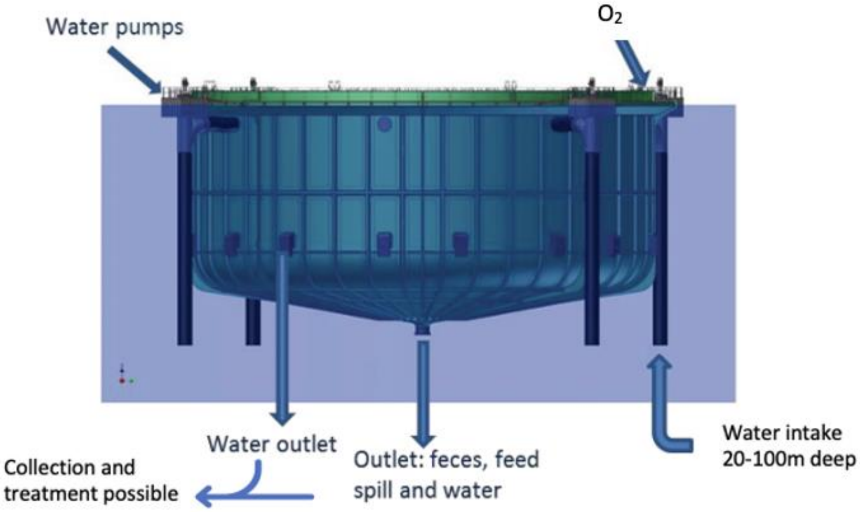

Figure 6. *Schematic of a solid-walled CCS with the option to collect solid waste and effluent water (Calabrese, 2017).*

The marine CCSs depicted in Figures 5 and 6 involve the continuous pumping of water from the surrounding water column from depths of 20-100 m below the floating structure (Boulet et al., 2010). To maintain optimal dissolved oxygen levels within the pen, liquid oxygen or air may be injected into the incoming water at 10-20m depths using ultra-fine bubble dispersers (Boulet et al., 2010). With intensive aquaculture productions such as that of commercially farmed salmon, pure oxygen is often preferred over air since oxygen requirements will increase with increasingly greater stocking densities. Thus, if atmospheric air is used, the gas solubility limit of the water is quickly reached with only ~21% oxygen capacity. However, if pure oxygen is used, “the natural saturation limit in the water [for oxygen] is increased by a factor of 4.8 compared to aeration with mere air” (*Aeration systems and pure oxygen in aquaculture, n.d.)*.

It should be noted that these marine CCSs also allow for the collection and process of effluent and solid wastes, but the mechanical systems involved with this, and the waste treatment options can vary (Boulet et al., 2010). SSAT (2019) suggests that ozone and ultraviolet effluent treatments “are the most applicable disinfection methods”.

1.1.7 Closed-Containment Land-based Salmon Aquaculture Systems

Land-based systems involve the installation of salmon culture tanks within enclosed buildings. These tanks receive a water supply that is treated to remove pathogens and contaminants and additional processes such as aeration and/or oxygenation is performed to ensure optimal water quality is maintained within the tank (SSAT, 2019; Boulet et al., 2010). The water may be pumped through the tanks on a flow-through or recirculated basis (Boulet et al., 2010). The flow-through land-based systems receive new water continuously, while recirculating aquaculture systems (RAS) allow for a portion of the effluent water, after the “adequate removal of carbon dioxide, ammonia, and suspended solids”, to be recirculated back into the system to decrease the load requirements of pumping new water into the tanks (Boulet et al., 2010**).**

Figure 7, below, shows the general layout and components of a land-based RAS where the incoming water undergoes mechanical filtration, ammonia removal, aeration, and oxidation to ensure environmental parameters within the tank meet salmon-rearing requirements. Like marine floating CCS, land-based CCS also has the option to collect effluent and solid wastes for further treatment (Boulet et al., 2010).

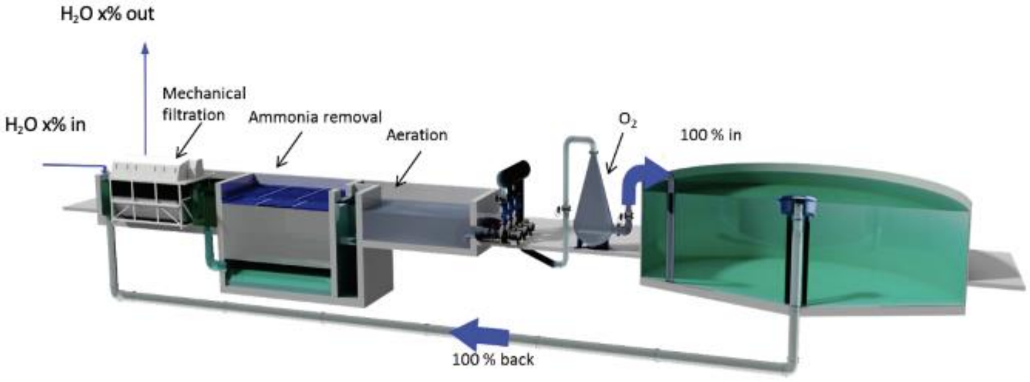

Figure 7. *General schematic of a land-based recirculating aquaculture system (RAS) where a certain percentage of water from the tank is replaced with new water while the rest is recirculated back into the tank (Calabrese, 2017).*

1.1.8 Marine CCS as an Alternative to ONPS

There are several alternatives to ONPS that could be considered for salmon farming in British Columbia. However, given the time constraints for my systematic literature review, I wanted to focus on the assessment of one alternative aquaculture technology. After review of literature such as Ayer and Tyedmers (2009), Nilsen et al. (2020), Stien et al. (2018), and Boulet et al. (2010), I determined that the focus of my review would be on marine CCS as an ONPS alternative. The reason for this choice is further discussed in this subsection.

Ayer and Tyedmers (2009)

Ayer and Tyedmers (2009) conducted a life cycle assessment (LCA) of the following aquaculture technologies in Canada, in increasing order of containment as follows: 1. marine net pens, 2. marine floating bags, 3. land-based flow through, and 4. land-based recirculating, with the intent of assessing their life cycle environmental impacts to the nearby ecosystem and the world at large (e.g., their contribution to global warming). They found that the higher the level of containment of wastes and diseases, the more complicated the infrastructure and energy inputs required per tonne of live-weight fish produced, with a generally direct increase in monetary costs. In order of cost, the CCS are as follows: marine net pens, marine floating bags, land-based flow-through, and land-based recirculating. This led to my hypothesis that if a phase-out of ONPS takes place, marine CCS may be a better alternative to ONPS over land-based systems. However, risks such as those associated with farmed fish escapes or accidental release of effluent from marine-based aquaculture technologies were not considered by Ayer and Tyedmers (2009). Since these are legitimate concerns associated with open net pens, the chances of these risks occurring, and the severity of their impacts should also be considered in future assessments of alternate aquaculture technologies.

Nilsen et al. (2020)

Nilsen et al. (2020) focused on directly studying Atlantic salmon growth and mortality rates, and the causes of post-smolt mortality in marine CCS facilities. They assessed fish growth rates by the measured increase in fish biomass at a specific water temperature over the grow-out period (a calculation that yields the thermal growth coefficient [TGC]). Whereas the fish mortality rates were measured by the number of fish mortalities observed weekly throughout the grow-out period.

The following are the growth (on the basis of TGC) and mortality rates Nilsen et al. (2020) observed:

- TGC of 3.03
- Cumulative 3-month mortality of 2.6%
- Cumulative total (inclusive of all 159 days of the trial) mortality of 3.6% (i.e., a monthly average of ~0.7%)

Nilsen et al. (2020) compared their trial results for farmed salmon growth rates in marine CCS to ONPS growth rates reported by Skaar and Bodvin (1993) and Mørkøre and Rørvik (2001). According to Skaar and Bodvin (1993), a moderate growth rate for ONPS was represented by a TGC of 2.1, Mørkøre and Rørvik (2001) notes that TGC may range from 1.24 to 4.95 in ONPS depending on the season. Nilsen et al. (2020) also observed seasonal fluctuations, but the average TGC they observed within their trial CCS pens (TGC of 3.03) was higher than what was considered moderate in ONPS (TGC of 2.1) by Skaar and Bodvin (1993). Thus, Nilsen et al. (2020) concluded that CCS-grown Atlantic Salmon had good growth rates.

Nilsen et al. (2020) compared their trial results for mortality rates to the historical averages reported by ONPS salmon farms in Norway. The annual mortality data from Norwegian ONPS salmon farms showed that the average monthly mortality rate for ONPS was approximately 1.3%. Since the average monthly mortality rate Nilsen et al. (2020) observed within their trial CCS pens was 0.7%, they concluded that CCS-grown Atlantic Salmon had "low to moderate" mortality rates when compared to ONPS-grown salmon. Nilsen et al. (2020) also noticed that failure to smolt and bacterial infections leading to ulcers and fin rot were among the main causes of mortality when grow-out was undertaken in marine CCS.

Nilsen et al. (2020) showed that it was possible to conduct commercial-scale salmon grow-out in marine CCS. Their study also emphasized the need to determine which CCS pen conditions may need to be more extensively focused on to improve fish welfare and in turn fish production.

Stien et al. (2018)

Since sea lice infestation within salmon farms was one of the main concerns with ONPS, the aquaculture technology to replace this system would need to address this issue. One way to mitigate pathogen transfer risk is through the elimination or minimization of the transfer pathway of the parasite via the ambient seawater outside of the pens (Frazer, 2009). Sea lice larvae have a positive phototactic response (Bron et al., 1993 as cited by Stien et al., 2018), so the main transfer pathway is through the upper levels (0-5 m) of water near the pen.

Stien et al. (2018) conducted a trial at a commercial fish farm in Nordland County, Norway, during which a barrier was placed around the net pens (Figure 8) to test its effect on pathogen transfer from the surrounding waters into the pens. The study revealed that by placing a semi-permeable sheeting, called sea lice skirts, around the upper portion of ONPS, sea lice infestation to salmon within the pen could be reduced by 80%. Thus, this study indicated a correlation between the addition of a barrier between the pen and the upper levels of the surrounding water column and a decrease in sea lice infestation within the pen.

Figure 8. *Schematic of an ONPS with the addition of a barrier known as a sea lice skirt (Wright et al., 2019).*

Though the main aim of Stien et al. (2018) was to study the effects of sea lice infestation within the pens and not the decrease of their transference to wild salmon, the assumption is that the probability of transfer to wild salmon likely decreases with the decrease in sea lice numbers within the pen. Though it is impossible to declare this risk of transfer to wild fish as being null with just the use of sea lice skirts, by increasing the level of containment through the addition of a barrier on the outside of the pen, the pathogen-transfer pathway between farmed salmon and juvenile wild salmon may be diminished.

Boulet et al. (2010)

All the analysis within the feasibility study of CCS salmon farming facilities by Boulet et al. (2010) was undertaken with assumptions that the system would be used within British Columbia’s aquaculture industry and thus all costs were considered in terms of the existing pricing within the province. The preliminary analysis for this study concluded that land-based RAS was the most financially feasible option of the closed containment technologies; hence, the rest of their study was primarily focused on the financial comparisons between ONPS and RAS

(Boulet et al., 2010). It should be emphasized that theirs was purely a general financial analysis and that all the available technologies require more research and trial at sites before actual investment. Boulet et al. (2010) notes that the DFO had trouble estimating realistic capital and operating costs for the marine CCS as the technology was in its developmental stages at that time. Since Boulet et al. (2010) were required to make many assumptions for these systems during their study, the exact margins of error for their evaluations of marine CCS are not known. Furthermore, their feasibility study of CCS was purely based on financial factors and did not account for environmental and social license costs which Boulet et al. (2010) states would also impact the profitability of the different fish farming systems.

1.2 Research Problem Statement

The need to transition away from ONPS aquaculture for salmon farms in British Columbia has become more evident (Cohen, 2012; Haya, 2001; Hall-Spencer and Bamber, 2007). One alternate option is the use of marine CCS (Nilsen et al., 2020) which, if undertaken properly, can provide a barrier to diseases and parasites between the farmed fish and the outside environment (Stien et al., 2018), and possibly reduce the amount of sewerage, waste, and deleterious chemicals released into the surrounding environment. These systems also have the potential of being cheaper and causing less environmental impact than land-based systems in terms of the overall infrastructure, materials, and resources they require (Ayer and Tyedmers, 2009). As such, CCS has the potential to make aquaculture more sustainable, thus warranting more research and assessments to determine their environmental impacts and commercial viability.

Thus, the main research question for my project was as follows:

> In what ways are floating nearshore CCS a sustainably viable option to replace saltwater ONPS currently used in British Columbia salmon farms?

To assist in answering the main question, the following sub-questions will be addressed:

- What are the environmental impacts of using a CCS and how does it compare to conventional ONPS?
- What are the difficulties and/or challenges relating to the commercial use of CCS?
- What are the scientific community's and public's perceptions towards CCS?

1.3 Project Objectives

Closed containment aquaculture may have the potential to be used as an alternative to the ONPS for Atlantic Salmon farming with the view that it might address some of the problems associated with the latter. The primary objective of this research was to determine the commercial viability of CCS in British Columbia while considering all three pillars of sustainability: environmental, social, and economic.

Lending to the primary objective, the secondary objectives are to:

- Assess the impact closed containment has on farmed salmon welfare
- Determine how stocking densities within nearshore CCS compares to ONPS stocking densities
- Determine the possible waste management and treatment options for CCS salmon farm effluent

1.4 Project Scope

This systematic literature review, conducted from September to December 2022, was undertaken as a student study project. During that time, I used online databases that were freely accessible to BCIT students. I limited the scope of my study to a comparative assessment of ONPS saltwater salmon grow-out systems versus the floating nearshore CCS.

To determine the viability of marine CCS salmon aquaculture, the environmental, social, and economic impacts of this system were considered and compared against existing OPNS aquaculture technology. The aquatic rearing of aquatic species other than Atlantic Salmon was considered outside the scope of this project. In addition, the need for policy or regulatory changes to adopt net pen-alternative salmon aquaculture systems was not addressed as part of this project. The purpose of this systematic review was to determine whether the commercial use of marine CCS would be a sustainable alternative to the saltwater ONPS that are currently used for Atlantic Salmon grow-out in British Columbia.

Chapter 2: Systematic Literature Review Methods

2.1 Reporting Guideline and Checklist

This research project was conducted as a systematic literature review of published and grey literature from September to December 2022. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 checklist (see Appendix 1), which outlines the necessities for various sections of a systematic review report, was used as the guide for this project. As this was an individual student review that was conducted over four months, a shorter period than usual for typical systematic reviews, some components of PRISMA 2020 were modified to better fit the timeframe and purpose of this project. Items 24-27 from the PRISMA 2020 checklist were not considered since they pertain to the registration of systematic reviews into the PROSPERO database and this review will not be registered.

2.2 Information Eligibility and Inclusion Criteria

During the proposal stage for this report, I determined that the timeframe of focus for the period of information publications would be constrained to the years 2008-2022. This is because the Canadian Science Advisory Report (2008) and the financial feasibility study by Boulet et al. (2010) are the two main reports referenced by the DFO concerning CCS. So, I wanted to focus on gathering information from literature than had been published since 2008. However, as the project progressed it became apparent that in order to gather more inclusive background information on salmon farming, ONPS, and CCS aquaculture technologies, the search range time frame needed to be expanded. Thus, I decided that I needed to include publications from 2000 to 2022.

Ultimately, I decided that the search range would not go further back than 2000 because the number of search results without the restriction had been too overwhelming for the timeframe of this review. Therefore, any relevant literature sources that I found resulting from my database search and which fell within the 2000-2022 timeframe were considered for initial screening. To gather historical information regarding salmon aquaculture in British Columbia for the "Introduction" section, the search range was expanded to include any years before 2000. However, this exception was limited to reports and documents published by branches of the Government of Canada or the Government of British Columbia.

The inclusion of any particular literature was considered based on language, content type, and full access to the text as opposed to just the abstract. Only literature that was in English or available with an English translation was considered for the study. To avoid biased viewpoints, newspaper articles were excluded during the literature search. Furthermore, eligibility was considered based on whether the literature was peer-reviewed and if its full-text version was freely accessible online to the public or using institutional login credentials (i.e., database texts that are available to registered BCIT students and faculty). Literature was not discriminated against based on data or study type, or study design during the search, and all were taken into consideration for screening.

2.3 Information Sources and Search Strategy

Due to time constraints and literature accessibility, the literature search for this systematic review was conducted through online databases alone. The following databases were used: BCIT Library (bcit.summon.serialssolutions.com), Science Direct (www.sciencedirect.com), Google Scholar (scholar.google.com), and EBSCO (www.ebsco.com). The databases and corresponding search strings along with any filters that were used during the search are summarized in Table 1. The number of results obtained from each search prior to any screening is also shown in Table 1. The terms that I chose were with the intent of focusing the search on nearshore CCS salmon aquaculture technologies. However, the search string varied with each database as it was catered to fit the different advanced search operations allowed by the databases (e.g., truncation and Boolean Operators). Advanced search operations were used to narrow down search results to what was relevant to this project while also ensuring that terms that were often interchangeably used within the industry such as "salmon aquaculture" and "salmon farming" would also be included.

Table 1. *Search databases and corresponding key-word search details for my systematic literature review search*

	Search String	**Filters**	**Number of Results**
BCIT Library	*closed* AND containment* AND salmon* AND aquaculture* OR farming**	• full text online • scholarly & peer-reviewed • published year 2000-2022	29
Science Direct	*(closed containment) AND salmon AND (aquaculture OR farming)*	• review articles • research articles • published year 2000-2022	103
Google Scholar	*floating "Atlantic salmon" (aquaculture OR farming) "closed containment"*	• include citations • published year 2000-2022	321
EBSCO	*closed containment salmon aquaculture OR closed containment salmon farming*	• peer-reviewed • published year 2000-2022	33

Sources that were retrieved outside of the listed online database searches included Department of Fisheries and Oceans Publications [DFO] (2009; 2021; 2022) Statistics Canada (2021), the Cohen Commission Reports (2012), AgriService BC (2022), Rosenau (2022). These were used to provide definitions of the terms such as "crustacean" and "aquaculture". Some of the documents affiliated with the federal or provincial governments were found through searches on the DFO and Statistics Canada websites (during September 2022) and the latest publications were retrieved whenever possible. The DFO and Statistics Canada website URLs are www.dfo-mpo.gc.ca/aquaculture/index-eng.htm and www150.statcan.gc.ca respectively.

One of the key sources of background information for my study included the findings from Commissioner B.C. Supreme Court Justice Bruce Cohen's *Inquiry into the Decline of Sockeye Salmon in the Fraser River* (Cohen, 2012). This report is often referenced in government and other publications regarding questions surrounding the potential impacts associated with British Columbia fish farming.

Rosenau (2022) is a presentation originally prepared by project advisor, Dr. Marvin Rosenau, for the British Columbia *Minister of Agriculture's Advisory Council on Finfish Aquaculture* and updated over the years. The graph adapted from Rosenau (2022) (Figure 2) also included Sockeye Salmon return data received from the Pacific Salmon Commission via recent email communications.

The sources that I used to define terms were found through Google Search. From the search results, online publications by reputable organizations such as the National Oceanic and Atmospheric Administration of the United States (NOAA), Food and Agriculture Organization of the United Nations (FAO), and/or online libraries were given preference.

2.4 Literature Screening and Selection Process

Although search terms were formulated with the intent of narrowing down the search results to yield only project-relevant literature, there were still numerous results that fell outside the scope of this project. Therefore, all results were first screened based on their title and abstract/executive summary to determine if the literature related to salmon aquaculture or CCS salmon aquaculture. Next, the title and abstract screened results were further screened based on visual scans of their full texts. To quickly perform these scans, the digital Find command function ("Control+F" or "Command+F" on a Mac) was used to locate the occurrences of keywords or phrases within the full text. On rare occurrences, where the Find command was not functional, the Table of

Contents of the document was manually scanned for keywords, and relevant sections were examined to determine source inclusion.

To gather material for the “Introduction” section, screening was based on the presence of key terms such as:

- salmon aquaculture in British Columbia
- environmental impacts of salmon aquaculture
- salmon aquaculture technologies
- open net pen salmon aquaculture
- closed containment salmon aquaculture

To gather material for the “Systematic Literature Review Discussion and Results” section, the literature screening was based on whether there was a specific focus on nearshore closed containment salmon aquaculture rather than just salmon aquaculture in the broader sense. The following are the key terms that were used to ascertain whether sources would undergo a more detailed full-text examination:

- floating closed containment salmon aquaculture
- semi-closed containment salmon aquaculture
- semi-closed cage aquaculture system
- rigid-walled closed containment aquaculture
- flexible-walled closed containment aquaculture
- fabric aquaculture cage
- salmon aquaculture life cycle assessment

2.5 Data Collection, Literature Appraisal, and Synthesis Methods

After the initial literature selection, their full-text versions were read in more detail. A literature review matrix in Microsoft Excel 2022 (Appendix 2) was used to track the relevant characteristics and findings presented by each of the selected studies. The reviewed studies’ significance and contribution to this project were also tracked within the literature review matrix through a column that was designated for notes on how each study’s findings related to my research questions. The sources were also grouped based on whether they contained information on introductory background information (which included information on ONPS), environmental impacts of CCS, environmental impacts of CCS from a life cycle perspective, fish welfare in CCS, and/or socio-economic aspects of CCS.

The sources tracked in the literature review matrix were critically appraised. Primary and secondary source quality was assessed based on how well research questions were articulated, whether they provided justifications for the research design and if the conclusions were clear and supported by the evidence presented in the study or review. The quality of tertiary sources was mainly assessed based on publisher and/or author reputability, source reputability, and the rationality of their statements

The synthesis of data collected from the selected literature was also aided by the literature review matrix (Appendix 2). The different columns in the literature review matrix helped to identify studies that had similar views, on topics relating to the research questions (presented in section 1.2), and those that were opposed

Chapter 3: Systematic Literature Review Discussion and Results

3.1 Overview

The literature that was reviewed in this study included research, reviews, assessment reports, and grey literature on nearshore marine closed containment salmon aquaculture. This review is separated into the following sub-sections: fish welfare in salmon aquaculture; environmental impacts of marine CCS compared to ONPS; social and economic impacts of marine CCS compared to ONPS.

3.2 Fish Welfare in Salmon Aquaculture

Literature involving fish welfare in salmon aquaculture is further subdivided into the following sections: the importance of fish welfare in salmon aquaculture; general factors that contribute to fish welfare; operational welfare indicators in CCS; fish welfare requirements in CCS; and harmful organisms within CCS.

3.2.1 The Importance of Fish Welfare in Salmon Aquaculture

Like many commercial productions, the success and profitability of farming is reliant on the resulting quantity and quality of the product. Since the end product of animal farming is derivative of the cultured animals, Noble et al. (2018) describes in their handbook on fish culture that good husbandry practices, such as maintaining and optimizing animal welfare, are important to stakeholders and ultimately affect the value of the product.

Taking fish welfare into account during the production of salmon culture normally promotes healthy fish (Noble et al., 2018). From a general economic point of view, healthy fish presumably equates to lower mortalities and higher quantities of fish. As per these criteria, such yields may result in better quality and more valuable marketable products, generating a better return on investments per unit of fish produced. Unhealthy fish and unreasonable rates of mortalities should be an economic concern to salmon farmers and investors. But there are also other stakeholders such as non-governmental organizations, regulatory bodies, and the general public that want these aspects to be kept at a minimum, as well (Noble et al., 2018).

Product Quality and Public Perception

A review conducted by Thorarensen and Farrell (2011) and a study by Calabrese et al. (2017) both focused on how various environmental parameters within CCS would impact salmon welfare. Thorarensen and Farrell (2011) focused on determining optimal levels of CO_2, NH_3, %air saturation, and stocking density within CCS while Calabrese et al. (2017) focused on establishing a stocking density limit for post-smolt Atlantic Salmon in CCS. They both found that rearing salmon in CCS that had parameters such as water quality and stocking densities outside of certain ranges would lead to increased stress on the fish in pens. These deleterious conditions could lead to an increase in unhealthy fish and fish mortalities and cost the producer monetarily.

The quality of the end product will also have an impact on the monetary value of salmon aquaculture as visual appeal, which is part of consumer satisfaction, will drive farmed salmon sales. Zhou (2016) conducted a study to assess how swimming speeds in CCS would affect Atlantic Salmon growth and, thus, fish quality. While observing correlations between growth rates and swimming speeds were of importance to Zhou (2016), another major objective was to determine the impact of salmon swimming speed on product quality. In his study, Zhou (2016) found that poor fish texture and fillet gaping, which yields an unattractive appearance to the final product, and unappealing flesh color, are among the main physical characteristics that may be the result of poor fish welfare due to lax husbandry during the farming process. Forcing the cultured fish to swim against a current (i.e., increasing their swimming speed), as compared to a still-water environment, helped address some of these issues (Zhou, 2016).

In a study conducted by Yip et al. (2017), they showed that consumers were influenced in their willingness to pay for sustainably farmed salmon by their perception of the systems used in salmon farming. Yip et al. (2017) compared integrated multi-trophic aquaculture (IMTA), a system that cultivates multiple species by mimicking “conditions of a balanced ecosystem [at] a farm site”, to CCS. They found that people were more willing to pay for IMTA products because they viewed the conditions within the farm as more “natural” compared to CCS.

The consumers’ perception of the farmed salmon product seems to be tied to fish welfare in that they want the farmed salmon they purchase to have experienced a life that was as similar as possible to that of wild salmon. Both Zhou (2016) and Yip et al. (2017) showed that fish welfare is an important aspect to consider in salmon farming as it can impact the quality of the product, the psychological perspective of the animal’s well-being, and, ultimately, the consumers’ salmon purchasing decision.

Standardized Product Certification

In a report to the federal Standing Committee on Fisheries and Oceans, Weston (2013) suggest that a way in which aquaculture companies may relay sustainable practices information to consumers and commercial distributors is through environmental certifications and labelling, and this may influence their purchasing decisions. Good fish-culture husbandry practices can assist in ensuring that product certifications take place.

The FISHWELL handbook by Noble et al. (2018), which is a publication that provides recommendations for fish welfare different production systems, and is based on reviewed scientific literature, also recognizes the importance of third-party standard certifications within the aquaculture industry. Internationally recognized organizations such as the Royal Society for the Prevention of Cruelty to Animals, the World Organization for Animal Health, and the Aquaculture Stewardship Council all have standards that promote fish welfare within the context of aquaculture by providing species-specific animal husbandry requirements (e.g., environmental quality, crowding, vaccinations, etc.). Through regulatory and policy requirements, for such aspects as health management plans, limits for mortality, and disease/pathogen monitoring, the subsequent environmental standard certifications can sometimes address animal safety and well-being (Noble et al., 2018).

The aquaculture standards can not only address fish welfare with regard to preventing inhumane farming conditions but also intervene in helping to prevent the spread of "infectious agents in international trade in aquatic animals" (Noble et al., 2018). An example of such an agent is the viral disease *Piscine orthoreovirus* which is now commonly observed in British Columbia's salmon farms but originated from Europe (Mordecai et al., 2021).

3.2.2 General Factors that Contribute to Fish Welfare

The FISHWELL handbook (Noble et. al, 2018) categorized the welfare needs of salmon in captivity into the following: the resources the fish require, their rearing environment, their physical health, and their ability to express behaviours typical of their species. According to Noble et al. (2018), the main resource fish require is nutritious food, and their environmental welfare needs refer to aspects such are being able to respire comfortably, and having access to water with adaptable temperatures, pH, and salinities which is also free from deleterious substances. Moreover, having surroundings that protect the fish from dangers which also have "low concentrations of harmful organisms (e.g., parasites, bacteria, and virus[es])" relates to the physical health needs of the fish (Noble et. al, 2018). Lastly, behavioural welfare needs refer to provisions such as access to social contact with other fish, rest, exploration opportunities, and being able to have behavioural control (e.g., controlling bodily movements in response to stress and fear) (Noble et al., 2018).

Figure 9, below, illustrates how salmon welfare needs connect to observable characteristics within the fish such as their appetite, stress, and growth, which can be assessed to determine fish welfare status. Studies like Øvrebø (2022), Moe (2017), and Nilsen et al. (2020), which are discussed in more detail in the other sections of this review (sections 1.1.7, 3.2.2, and 3.2.4 respectively), observe these characteristics relating to fish welfare to evaluate the adequacy or limitations of novel salmon aquaculture systems such as CCS.

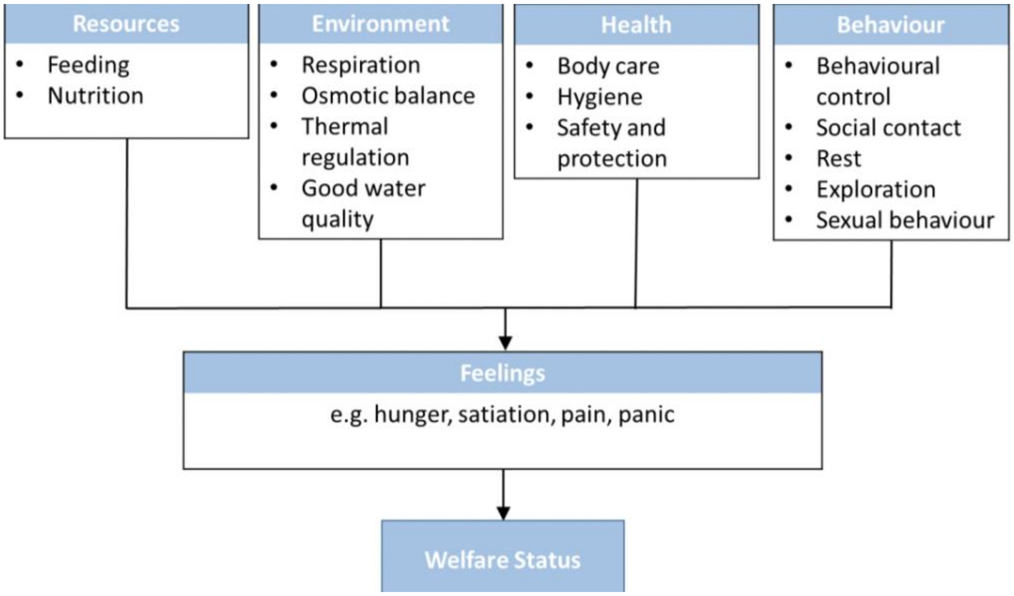

Figure 9*. Salmon welfare needs categorized into resource availability, environmental conditions, fish health, and the ability to express behaviours (Noble et al., 2018).*

3.2.3 Operational Welfare Indicators in CCS

The observable characteristics of fish that correlate to their well-being may be referred to as fish welfare indicators. Within the context of fish aquaculture, the term "operational welfare indicators" (OWIs) is often used to describe factors that may be utilized to measure fish welfare in a farm setting (Noble et al., 2018). These factors are based on the resources, environment, health, and behaviour categories previously presented in Figure 9 (section 3.2.1).

Figure 10, below, depicts how the applicable OWIs are split into categories based on indirect ("Environment Based") factors relating to the conditions within the CCS pen, and direct ("Group Based" and "Individual Based") factors relating to how the fish are responding to their environment. "Environment Based" OWIs relate to aspects within the farm such as oxygen level, turbidity, pH, and water velocity. These include factors that can be observed using environmental-parameter probes and other automated measurement devices. "Group Based" OWIs (e.g., appetite, growth, swimming behaviours, etc.) and "Individual Based" OWIs (e.g., fin damage, sea lice, deformities, etc.) may require installations of underwater cameras within the systems and/or include physical examinations of the fish in and from the pens (Noble et al., 2018).

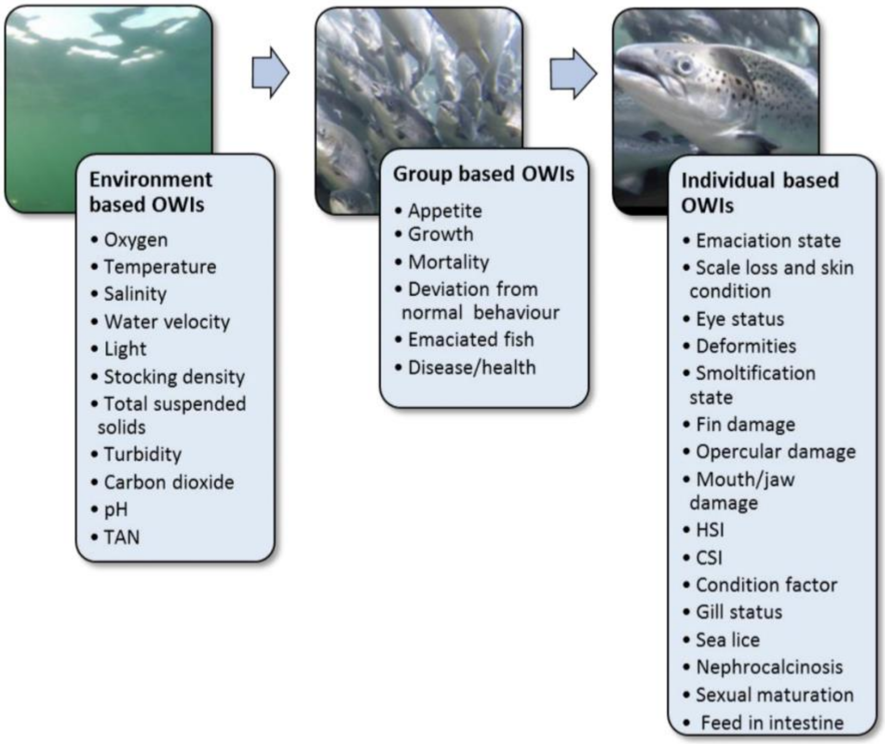

Figure 10. *Environmental, group, and individual based operational welfare indicators for salmon farmed in semi-closed containment systems (Noble et al., 2018).*

Some OWIs that apply to ONPS are also applicable to CCS aquaculture (Noble et al., 2018) The differences may be magnified in the latter due to the generally much-greater stocking densities in CCS. However, since enclosed aquaculture systems are structurally different from ONPS in that there is now a barrier between the farm and the aquatic environment, and water is being pumped in from several feet under the enclosure (Boulet et al., 2010), there are some OWIs that need to be considered more extensively with CCS (Noble et al., 2018). For example, the enclosed nature of CCS and high fish stocking densities increasingly promote the buildup of deleterious components such as carbon dioxide (CO_2) and organic wastes within the system. Thus, environmental-based OWIs such as CO_2, oxygen, pH, turbidity, total suspended solids, water pumping velocity, and total ammonia nitrogen (TAN) will need to be monitored more closely and mechanisms put into place to maintain these within optimal ranges (Noble et al., 2018).

An example of a Group-Based OWI for CCS that may differ from ONPS is the way fish behave (Noble et al., 2018). A comparative study (Moe, 2017), undertaken for salmon in Preline (a type of floating raceway CCS) and salmon in ONPS, showed that the salmon in the former tended to swim against the current without changing positions within the systems which the study found to be different from the behaviour observed in ONPS. Noble et al. (2018) suggests that these behavioural differences in swimming activity within systems may be specific to the raceway or pen type. Thus, fish behaviours within circular CCS may be similar to that exhibited within circular ONPS.

An example of an individual based OWI that may require more monitoring in CCS is nephrocalcinosis (Noble et al., 2018). This is a disease in farmed salmon that has been associated with increased levels of CO_2 and leads to “the accumulation of calcium and magnesium deposits in the kidneys” (Klykken et al., 2021).

According to a review published by Eriksson et al. (2017), influent water quality is relatively stable in CCS, but there is a higher possibility for water quality within the farm to reach sub-optimal levels and compromise the health of the farmed fish. Eriksson et al. (2017) noted that since water is pumped from depths greater than 15m below the aquaculture farm, CCSs have more stability with their influent water quality, compared to ONPS, with regards to water temperature, oxygen content, parasites, and salinity. However, because of the enclosed nature of CCS, and higher fish stocking densities, there may be greater chances that the water within the containment will fall into unhealthy ranges during its residence time (Eriksson et al., 2017). This could lead to the possibility that more deleterious fish welfare incidents may occur in CCS compared to ONPS. Thus, there may need to be comparatively more extensive monitoring of OWI parameters for CCS.

3.2.4 Fish Welfare Requirements in CCS

During the literature review search, I found that there are few published peer-reviewed studies that establish good husbandry practices for Atlantic salmon in CCS. The only studies that I found included Thorarensen and Farrell (2011), Calabrese (2017), and Sveen et al. (2016). Other closed containment salmon aquaculture studies (e.g., Nilsen et al., 2020; Clarke et al., 2018) that were focused on studying different aspects of CCS salmon aquaculture production used the results from the above-mentioned main studies as guides to assess the likely-required environmental conditions within closed containment systems to maintain good fish health.

Thorarensen and Farrell (2011)

In their literature review on aquaculture salmon farming, Thorarensen and Farrell (2011) found that the water in the pens should be at least 85% air saturation[1] while the CO_2 concentrations needed to be below 10 mg/L and dissolved NH_3 below 0.012mg/L. Moreover, the stocking density should beat < 80 kg/m^3 to maintain good growth and survival rates for salmon in CCS.

Thorarensen and Farrell (2011) also reviewed literature on salmon aquaculture, and they suggested that growth rates within CCS may improve by increasing % air saturation to between 70-100%. However, they also noted that the addition of oxygen adds to the operational costs of the system. Therefore, the benefits of this increase in the growth rate "must be weighed against the cost of adding supplemental oxygen" (Thorarensen and Farrell, 2011). Additionally, their review found that oversaturation with oxygen could lead to adverse effects, thus concluding that the upper limit of air saturation should be approximately 120%.

Calabrese (2017)

Calabrese (2017) assessed the effect different stocking densities in CCS had on fish welfare factors. This included various parameters such as cortisol levels, growth, and morphological damage and how mass-specific water flow (SWF) related to oxygen consumption in post-smolt Atlantic Salmon.

Calabrese's (2017) results were based on data collected from 8-week trials of post-smolts in flow-through seawater systems which they designed to "simulate predicted conditions in [a] sea-based closed system in southern parts of Norway". Calabrese (2017) noted that the transfer of post-smolts from freshwater to seawater pens is typically a stressful event for the fish (and a sensitive time in the production cycle) as they adjust to the new environment. However, the post-smolts used in Calabrese's (2017) trials were seawater acclimated before the start of the trial.

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[1] *Dissolved oxygen is often expressed in terms of air saturation in the aquaculture industry (Thorarensen and Farrell, 2011). Thus, any reference to % air saturation within my literature review is in relation to dissolved oxygen content within the water column of the salmon pen.*

One aim of Calabrese (2017) was to determine the maximum stocking level achievable in CCS for post-smolt rearing before it caused significant harm to fish performance or welfare. After assessing various stocking densities, including 25, 50, 75, 100, and 125 kg/m^3, Calabrese (2017) concluded that densities up to 75 kg/m^3 were possible in CCS without negative impacts on fish welfare. This finding was similar to that of Thorarensen and Farrell (2011) which suggested that stocking densities of salmon in CCS should be kept below 80 kg/m^3.

Mass-specific water flow (SWF) relates to the rate at which water is being pumped through the CCS, and since pumping water requires energy inputs, keeping the SWF as low as possible is ideal from a cost perspective. However, the lower the SWF in CCS, the more prolonged the residence time of the water within the pen, leading to respiration-related CO_2 concentrations in the water to increase (Calabrese, 2017). Hence, another aim of Calabrese (2017) was to determine the optimal SWF in CCS to maintain good post-smolt welfare.

When the environmental characteristics within the salmon farm change (e.g., fluctuations in levels of CO_2, pH, NH_3, etc.), responses are triggered in the fish to adapt to the change and maintain body homeostasis. Increasingly extreme conditions will cause the salmon to expend more energy to survive and grow, leading to increased stress within the fish if they are not able to match the response required by the changing environment (Calabrese, 2017). These changes by the salmon to increasingly sub-optimal conditions are what is referred to as physiological regulatory responses in fish.

To determine the required SWF in CCS, Calabrese (2017) tested various SWFs, including 0.2, 0.3, 0.4, and 0.5 L kg fish^{-1} min^{-1}, and observed the physiological regulatory responses salmon had to the changes in pen condition associated with the different SWFs. Through this trial, Calabrese (2017) found that although growth was maintained at a lower SWF of 0.2 L kg fish^{-1} min^{-1}, oxygen consumption increased as a physiological regulatory response to the increased CO_2. An increase in oxygen consumption by the fish in the pen means that more of this gas needs to be supplied to the system to maintain optimal growing conditions, thereby increasing the energy consumption of the facility and in turn the costs associated with rearing salmon in CCS (Calabrese, 2017). Therefore, Calabrese (2017) concluded that maintaining an SWF above 0.3 L kg fish^{-1} min^{-1} would be ideal for post-smolt rearing in CCS. The findings from Calabrese (2017) also suggested that using lower SWFs may cause fish welfare issues. This included deleterious conditions associated with skin quality such as damage to epithelia. But the specifics of these were not established within this study as it was outside its scope.

Sveen et al. (2016)

Sveen et al. (2016) assessed the impact of fish stocking density and SWF in CCS through a 10-week study in the Industrial Laboratory (ILAB) in Bergen, Norway. They looked at the skin properties of Atlantic salmon in CCS and observed that lower SWF (0.2-0.3 kg fish^{-1} min^{-1}) led to increased "transcription of genes associated with immune responses and mucus production in the skin". Sveen et al. (2016) did not conclude this change in the fish skin as a negative impact but only stated that the change was likely a response to increased stress associated with the lower SWF. Thus, the findings of Sveen et al. (2016) did not support the suggestion by Calabrese (2017) that lower SWFs may lead to damaged fish epithelia.

Summary of Environment-Based Requirements for CCS

According to Noble et al. (2018), many of the pen parameter requirements for CCS are the same as those for ONPS, but due to the enclosed nature of CCS, accumulations of certain components (e.g., organic matter and CO_2) within the pen may lead to greater deviations from optimal salmon rearing conditions in CCS compared to ONPS. Therefore, some environment-based parameters of particular importance in CCS, according to the literature reviewed (Thorarensen and Farrell, 2011; Calabrese, 2017; Sveen et al., 2016; Noble et al., 2018), are presented in Table 2 along with their corresponding requirements.

Table 2. *Environment-based requirements to maintain Atlantic salmon welfare within CCS*

Parameter	**Requirement**	**Literature Source**
dissolved oxygen expressed as % air saturation	minimum of 85% and not over 120%	Thorarensen and Farrell (2011)
CO_2	needs to be below 10 mg L^{-1}	Thorarensen and Farrell (2011)
NH_3	needs to be below 0.012mg/L	Thorarensen and Farrell (2011)
fish stocking density	needs to be below 80 kg/m^3; ideally 75 kg/m^3	Thorarensen and Farrell (2011); Calabrese (2017); Sveen et al. (2016).
mass-specific water flow	should be above 0.3 L (kg fish^{-1}) min^{-1}	Calabrese (2017); Sveen et al. (2016); Thorarensen and Farrell (2011).
pH	Greater than 7.2-7.4	Noble et al. (2018)
total ammonia nitrogen (TAN)	Below 1-2 mg L^{-1} or Below 5-10ug L^{-1} NH_3-N	Noble et al. (2018)

3.2.5 Harmful Organisms Within CCS

Harmful organisms such as parasites and pathogens have been observed within salmon aquaculture systems in British Columbia (SSAT, 2019). Parasites are defined as organisms that live inside or on a larger organism of different species (known as the host organism) from which the parasite acquires most of its nourishment, often causing harm to the host organism (Dimijian, 1999). Whereas pathogens encompass a broader scope of harmful organisms (e.g., bacteria, fungi, viruses, etc.) that infect and cause diseases in the host organism (Dimijian, 1999). Parasites and pathogens commonly found in ONPS include the following: sea lice, which cause skin wounds, and lesions in salmon (Frazer, 2009); *Piscine orthoreovirus* which causes reduced fitness in salmon (Morton et al., 2017); and infectious salmon anemia virus (ISAv) (Cohen, 2012).

Some sources (Rud et. al., 2017; Osdal, 2021; Nilsen et al., 2017; Noble et al., 2018) that recounted marine CCS trials, noted the presence of harmful organisms within these systems. According to these reviewed sources, the harmful organisms observed in marine CCS include (but are not limited to) sea lice, *Tenacibaculum* spp., *Aliivibrio* spp., and jellyfish. These organisms and their presence in marine CCS along with possible ways to manage such infestations in CCS are further discussed in this subsection.

Note: the risk of transference of harmful organisms from CCS to wild salmon outside the pen is addressed later in this review (section 3.3.1.).

Parasites

Sea lice (*Lepeophtheirus salmonis* and *Caligus elongatus*) infestations are a prominent issue in ONPS (Frazer, 2009). Many salmon parasites and pathogens of concern, including sea lice, exist most often at ocean depths of 0-5 meters from the surface of the water (Eriksson et al., 2017). The view has been that by excluding contact with the fish inside (or outside) of the pens the source of infection might be reduced or eliminated. For example, Stien et al. (2018) observed an 80% reduction in sea lice infestations within salmon pens by adding sea lice skirts to ONPS (Figure 8,). Thus, by further decreasing the interaction between the salmon farm and this top layer of ocean water, one of the main expected benefits of CCS is further reductions in sea lice infestations within salmon farms.

Nilsen et al. (2017) observed sea lice infestations over three years of Atlantic salmon production in marine CCS (with a water intake depth of 25m) and used an ONPS for reference. The water which was pumped into the CCS during this study was not filtered or treated to remove sea lice, yet Nilsen et al. (2017) observed that the sea lice abundance was close to zero in the closed pens. Nilsen et al. (2017) did, however, eventually observe more sea lice after fish were transported between cages (suggestive of contamination from surface water) and when CCS was stocked with fish from open pens. However, the sea lice abundance within CCS remained significantly lower than that of ONPS even after exposure to sea lice. Notably, Nilsen et al. (2017) did not find signs of lice reproduction after exposure. They attributed this to a lack of mates due to the low initial abundance of lice and the possibility that the larval lice were being flushed out of the pen with the water flow before they had a chance to hatch. Thus, none of the CCS in the study (Nilsen et al., 2017) required any sea lice treatments to keep infestations below Norway's legislative requirements. Ultimately, Nilsen et al. (2017) concluded that the results from their study indicated that marine CCS "with a fixed intake depth below the vertical dispersion range of infective copepodites provide sufficient protection against sea lice".

Øvrebø et al. (2022) undertook a benchmark study of Atlantic Salmon welfare and growth in CCS in relation to pathogens/parasites. They also observed a similar trend in sea lice infestations within CCS as Nilsen et al. (2017) did with CCS, and the sea lice infestations were lower in the pens which had more containment than in the reference ONPS. Therefore, the results from Nilsen et al. (2017) and Øvrebø et al. (2022) corroborate the expectation that sea lice infestations in Atlantic Salmon farms could be lowered if the pens were operated with some level of enclosure as suggested by Stien et al. (2018).

Pathogens

Pathogens can enter CCS through the intake water if it is not treated. Further, diseased juvenile fish stocked into the pens and/or other pathogen-carrying organisms (vectors) that may enter the pen, can also transmit deleterious organisms to the rearing fish (Noble et al., 2018). To further compound this issue, the microbial films that form on components of CCS, due to biofouling, and the biofilters used in CCS might act as reservoirs for these pathogenic organisms and lead to their proliferation within the pen and infect the salmon therein (Rud et al., 2017).

Potential pathogens that were observed within CCS during post-smolt rearing trials include *Tenacibaculum* spp., and *Aliivibrio* spp. (Rud et al., 2017; Osdal, 2021). These organisms were referred to as "potential pathogens" because their exact pathogenesis (contribution to disease development) was unknown. However, their bacterium isolates or other bacteria with similar virulent lineage have been found during investigations of disease outbreaks, suggesting that the organisms in question may have contributed to the outbreak (Rud et al., 2017). *Tenacibaculum* spp. are bacteria that have been associated with tenacibaculosis (an ulcerative disease in salmon) in that it has been the “most commonly isolated bacterium from Northern Norwegian salmon farms during tenacibaculosis outbreaks” (Småge et al., 2018). On the other hand, *Aliivibrio* spp. are bacteria that have been associated with “cold-water vibriosis, a hemorrhagic septicemia of salmonid fish” (Nørstebø et al., 2018).

Both Rud et al. (2017) and Osdal (2021) investigated the presence of bacterial microbiota in CCS during the first few months after post-smolt transfer into the pen as juvenile salmon are deemed as being the most sensitive to diseases and infections during this period in the salmon farming process. Rud et al. (2017) studied the microbiota of both the water and biofilms in CCS for potential pathogens that are commonly found in the sea based on the Norwegian Fish Health Report of 2014 (Bornø and Linaker, 2015 as cited by Rud et al., 2017). Whereas Osdal (2021) conducted pathogen screening in CCS and ONPS focusing on *Tenacibaculum* spp. to determine if adding an enclosure to the open pens could reduce the presence of this bacterium within the pen. From their study, Rud et al. (2017) noticed an increase in several potential pathogens in CCS including *Tenacibaculum* spp. and *Allivibrio spp.*, but no symptoms of diseases associated with these bacteria were observed in the salmon during their trial period. Since Osdal (2021) monitored an ONPS along with CCS, they were able to make comparisons between the two systems and found that *Tenacibaculum* spp. was higher in the salmon reared in ONPS. Thus, Rud et al. (2017) confirmed that potential pathogens could still be present in marine salmon farms even if they are operated as CCS, while the results from Osdal (2021) postulated that the addition of an enclosure to ONPS could reduce the levels of pathogens (in the pen) which were transmitted through the water from the ambient aquatic environment.

Other Harmful Organisms

A non-pathogenic, yet harmful organism that was observed in a CCS was jellyfish (Noble et al., 2018). In the S-CCS that was observed by Noble et al. (2018), many small jellyfish had made their way into the farm through the inlet pipes, and their presence, along with their ability to sting, was noted as causing stress in the farmed salmon (noticed through a lack of appetite) and eventually, high numbers of fish mortalities. According to a study (Ferguson et al., 2010) cited by Noble et al. (2018), jellyfish are not a problem specific to CCS as they can also enter ONPS, but the enclosed aspect of CCS may cause the jellyfish to remain in the closed pen for a longer time compared to an open pen. The species of small jellyfish (approximately 13mm in size) observed by Ferguson et al. (2010) was *Phialella quadrata,* and they noted that the main way the jellyfish harmed the fish was by stinging them. In addition, Ferguson et al. (2010) found that the jellyfish could also be vectors for Atlantic Salmon pathogens; *Tenacibaculum maritimu* was present in the mouths of the jellyfish in this study. Consequently, not only could the jellyfish cause bodily harm to the fish by stinging them, but the resulting wounds could also act as pathways for pathogens such as *T. maritimu* to enter the fish population within the pens.

Management of harmful organisms within CCS

Although the risk of parasites and pathogens may be reduced by pumping water from depths below 5 meters (Eriksson et al., 2017), studies such as Rud et. al. (2017), Osdal (2021), and Nilsen et al. (2017) show that their presence in salmon aquaculture pens is not eliminated. There is still potential for some harmful organisms to enter through the influent stream in CCS and from exposure to diseased fish or other disease-carrying organisms that may enter the pen.

Since one of the pathways through which harmful organisms are introduced into CCS is the influent water streams, monitoring of outside waters for organisms and the use of intake filters is recommended by Noble et al. (2018) to reduce this risk. The risk of pathogens within CCS may be further decreased by subjecting the influent water to treatment. For example, Justad (2021) studied the ultraviolet UV inactivation of water pathogens, including ISAv, *Moritella viscosa* (a gram-negative bacterium that causes Winter Ulcer disease in salmon), and the ectoparasite *Lepeophtheirus salmonis* (sea lice). With the UV doses used by Justad (2021), only *Moritella viscosa* could be made ineffective to a desirable level of 99.9% (3-log). The other pathogens that were studied were only inactivated to lower extents (2.59-log for ISAv and 47.1% mortality rate for the sea lice) and these were not considered to be sufficiently impactful rates. Notwithstanding the work that was undertaken by Justad (2021), more extensive research is required in the future to determine optimal UV dosages that could possibly provide 3-log inactivation of several pathogens of interest.

The problem of organisms, such as jellyfish, entering CCS might be alleviated by using screens. But the sizes of these problematic organisms need to be considered when deciding on appropriate screen mesh sizes. Noble et al. (2018) indicated that for the screens that were used in the S-CCS study they observed that jellyfish still made their way into the pen. This suggests that the mesh size of the screen that was used to filter out this pest may have been too large. Noble et al. (2018) also noticed that jellyfish bits had clogged the pump intake screens, causing diminishing water qualities within the pen, so regular monitoring of the screens may also be necessary with marine CCS to keep system operations functioning properly.

Due to search limitations such as the publication time (2000-2022) and restriction to certain online databases, the literature obtained from the searches did not encompass all the relevant harmful organisms that may be encountered by Atlantic salmon in CCS in British Columbia. For instance, the literature search for this systematic review did not yield many studies which focused on viruses within CCS. However, as discussed in section 1.1.4 of this review, viruses such as infectious salmon anemia virus (ISAv) and *Piscine orthoreovirus* are known to occur in ONPS salmon farms (Cohen, 2012; Morton et al., 2017). Therefore, the literature reviewed here showed that the risk of such organisms is still present within the pen even with added enclosures. Thereby indicating the need for further research into the specifics of which organisms (that cause harm to salmon) are likely to occur in marine CCS in British Columbia. This information will be useful during risk assessments of CCS and when creating risk management plans for harmful organisms within CCS.

3.3 Environmental Impacts of Marine CCS Compared to ONPS

Literature involving the environmental impacts of marine CCS compared to ONPS is further subdivided into the following sections: disease and/or parasite transmission to wild salmon; waste management; fish escapes and wildlife interactions; and environmental impacts of CCS from a life cycle perspective.

3.3.1 Disease and/or Parasite Transmission to Wild Salmon

As Nilsen et al. (2017) and Øvrebø et al. (2021) indicated, having a barrier that separates the farm from its surrounding aquatic environment (as with CCS) diminishes a significant route of sea lice transmission which occurs in ONPS through the free flow of water (this includes transmission into and out of the pen). Since replacing ONPS with marine CCS has the potential to curb sea lice infestations within pens (Nilsen et al., 2017), the risk of transmission of sea lice from CCS-farmed salmon to wild salmon is accordingly decreased as well. Thus, further controls to reduce sea lice transmission from marine CCS to the outside aquatic environment may not be needed.

Although pumping the intake water for marine CCS from greater than 5m below the pen helps to decrease sea lice infestations, Rud et. al. (2017) and Osdal (2021) note that pathogens, such as *Tenacibaculum* spp. and *Allivibrio spp*., that may cause diseases in salmon could still persist in marine CCS. Hence, the transfer of salmon diseases from CCS to wild salmon through pathogens such as bacteria and viruses may be deemed a greater risk than the transmission of sea lice. The literature search results for this systematic review did not yield many studies which focused on assessing the transmission potential of harmful organisms (other than sea lice) from marine CCS to wild salmon. Therefore, more research on these pathogens, their performance within marine CCS and their pattern of dispersion if they were released along with CCS outflows, may be required to better assess this risk posed by marine CCS on migrating juvenile salmon.

If the risk of parasite or pathogen transfer to wild salmon is deemed high enough to warrant the use of risk control measures, engineering controls such as the treatment of outflows from CCS could possibly be utilized (SSAT, 2019). In a report prepared for the DFO (SSAT, 2019) on Canadian and global developments in salmon aquaculture technology, effluent treatment applications such as those using ozone or UV were noted as being used for land-based CCS, but for marine CCS, effluent treatment was deemed "possible in [the] future, but... not developed at economical stages yet". A report by Marshall (2003) referenced personal communications with Mariculture Systems, a company that focuses on developing novel aquaculture technologies, which mentioned that the company had been working on a filter system to strain out sea lice and bacteria from both influent and effluent streams of marine CCS. However, the results of this development or further details on its design could not be found online; the lack of published information on this filter system may contribute to the statement by SSAT (2019) that such treatments for marine CCS have not been made economically feasible yet, but it could also be that this is proprietary information because marine CCS is considered to be a relatively new technology that is still under development.

3.3.2 Waste Management

In a review, Eriksson et al. (2017) describes that the organic wastes from a salmon farm, such as salmon faeces and uneaten feed, may cause localized dissolved oxygen depletion and nutrient loading (e.g., the release of phosphorous and/or nitrogen from the fish feed) which may cause algal blooms and impact benthic organisms near the pen. Eriksson et al. (2017) also discusses how the magnitude of the risks associated with waste release into the aquatic environment will depend on the location of the farm as different areas have certain waste loading limits depending on the local characteristics such as water currents and native organisms. For example, a study by Kutti et al. (2007) observed that most of the waste material from an ONPS salmon farm in Norway, located in waters 230 m deep within a fjord system, would settle within 250 m of the farm. The phosphorous levels in the sediment were noted as being elevated but the total organic carbon and organic nitrogen (within 250m) were not elevated. Kutti et al. (2007) concluded that the presence of high bottom currents in the area, leading to resuspension and further dispersion of settled waste, coupled with the high decomposition capacity of the benthos contributed to their finding that the waste released did not exceed the loading capacity for that benthic environment during the farm's production cycle. Both Eriksson et al. (2017) and Kutti et al. (2007) suggests that local aquatic and benthic conditions will be important to consider when determining the waste management requirements and the extent of controls to be used by the salmon farm.

Several sources (e.g., Nilsen et al., 2017; Eriksson et al., 2017) have observed that a benefit of using CCS over ONPS is that CCS allows for the collection of settleable waste feed, feces, and other organic matter such as dead fish. Supporting this observation, Weston (2013) in a report on *Closed Containment Salmon Aquaculture* presented by the Standing Committee on Fisheries and Oceans noted that the floating CCS developed by AgriMarine was "successful in removing 90% of settleable wastes, which, in an open-net pen aquaculture system, would otherwise settle to the ocean floor or be dispersed by ocean currents". Hence, replacing ONPS with CCS for salmon farming may reduce the risk of environmental impacts on the seabed that is typically associated with the free release of wastes that occurs with ONPS (Nilsen et al., 2017; Eriksson et al., 2017).

There are several designs that have been incorporated for CCS, especially in regard to collecting waste material. Most studies (e.g., Zhou, 2016; Nilsen et al., 2020) had set up their marine CCS trials to collect settleable aquaculture wastes at the bottom of the CCS and filter this waste through a drainage system at the bottom. However, a study by Klebert et al. (2018), which focused on the measurement and simulation of waste particle activity and removal efficiencies in marine CCS, found that there is also the option of combining bottom waste collection with drains placed on the upper sides of the CCS.

Figure 11, below, is a schematic of the CCS observed by Klebert et al. (2018) which included an ellipsoidal tarpaulin tank with four outlets situated below the water surface and one bottom outlet. Using computational fluid dynamics and numerical models, Klebert et al. (2018) created a CCS simulation and discovered that the preferable mechanism of removal for particles less than 500 μm (which may not be settable) was through upper-side drains while the bottom drain was preferential for larger particles.

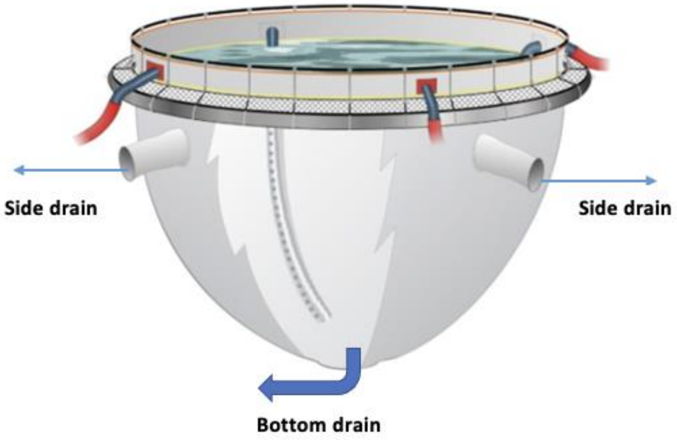


Figure 11*. An ellipsoidal closed containment aquaculture system made of tarpaulin mounted on a floating collar with side and bottom drains for waste collection (Klebert et al., 2018).*

After the settleable solids are collected in CCS facilities, this material may be further dewatered to create a waste sludge using various filters and/or sedimentation methods which often result in up to 20% water removal (Eriksson et al., 2017). The floating CCS by AgriMarine, which was described by Weston (2013) as being able to manage 90% of settleable wastes, used a waste management system of collection from the bottom of the tank and a subsequent "waste removal system" which used filtration as the mechanism for waste removal as shown in Figure 12 below.

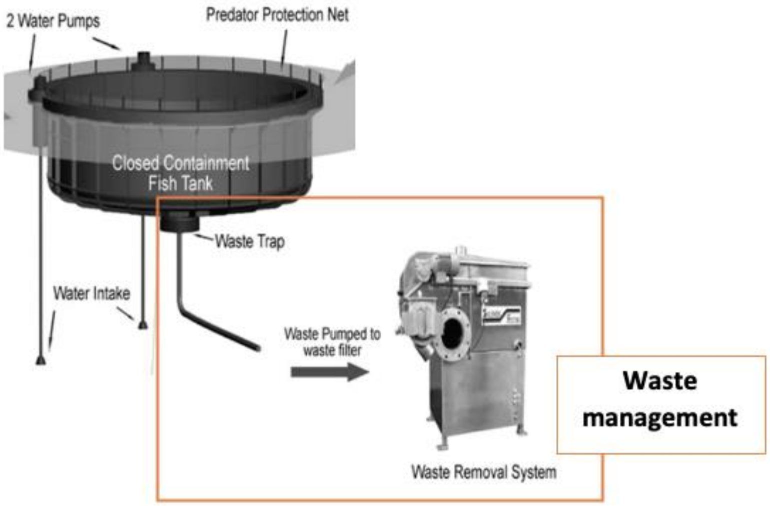


Figure 12. *A solid-walled closed containment system developed by AgriMarine Industries Inc. Waste removal is demarked using an orange border (Weston, 2013).*

The waste sludge generated after the filtration of aquaculture wastes could be further utilized in other industrial applications. Eriksson et al. (2017) and Bohnes and Laurent (2021) both noted that the waste sludge generated after the filtration of aquaculture wastes could be processed and used as fertilizer for terrestrial-based plant growth. However, Eriksson et al. (2017) also notes that the aquaculture waste from nearshore farms may be high in salt content, which may pose a hindrance to its use in fertilizers.

Another way to make use of the waste sludge generated by salmon aquaculture is to produce biogas from it (Eriksson et al., 2017). A study by Moreno (2016) explored the environmental impacts associated with biogas production from fish waste in Norway through a life cycle assessment (LCA). Moreno (2016) found that there was significant potential for reducing the environmental impacts of salmon aquaculture by incorporating a biogas value chain into salmon production. This conclusion was on the basis that the LCA showed a reduction in global warming potential for CCS (-206 kg CO2 eq) with the addition of biogas production and its subsequent replacement of fossil-fuel-based energy sources. Thus, the biogas generated from fish waste can potentially be used as fuel in energy generation (Moreno, 2016), perhaps even to help power the CCS facility. This approach of taking waste from one industry, recycling it, and using it as input once again is a way in which a more “circular” approach to industrial practices may be adopted, thereby further promoting sustainability.

Besides solid organic material, other components within the effluent from salmon farms include dissolved organics from the degradation of the carbon-based waste and the chemicals used for pathogen treatments (Eriksson et al., 2017). From studies such as Hall-Spencer and Bamber (2007) and Haya (2001), it was evident that the release of chemicals used to curtail sea lice infestations within ONPS was of particular concern to organisms like crustaceans and maerl. Water treatments such as those employed by wastewater treatment plants (e.g., biofiltration and chlorination) may be options to further treat the wastewater from CCS salmon farms beyond just the removal of settleable solids. However, Braaten et al. (2010) (as cited by Moreno, 2016) notes that the treatment of dissolved organics is not feasible for salmon farms and only particulate waste is dealt with. Similarly, Eriksson et al. (2017) mentions that dissolved components from CCS are mostly passed into the environment and feasible treatment options for this material within the context of the aquaculture industry are still to be developed. The lack of treatments for the dissolved components may be because replacing ONPS with marine CCS decreases sea lice and other diseases which “minimizes or eliminates [the need for] therapeutants and treatments” which in turn decreases their release into the aquatic environment (SSAT, 2019). Furthermore, CCS allows for the collection of a majority of the solid wastes, so the overall waste material being released from the farm would be significantly less than what would be released if the farm was operated using ONPS.

3.3.3 Fish Escapes and Wildlife Interactions

Several reports and studies (Cohen, 2012; SSAT, 2019; Nilsen et al., 2017) have recognized farmed salmon escaping as one of the environmental concerns related to ONPS salmon farming. In *Escape prevention for farmed fish* (2020) the DFO notes that to minimize the risk of salmon escaping from marine aquaculture facilities, containment systems should:

- be able to endure weather and ocean conditions that are typical of the farm site location and the possible occurrences of extreme events should also be considered.
- be examined and monitored consistently to ensure that the integrity of the floating structure is maintained. This includes looking for any tears or holes that might be present in the netting.

Chadwick et al. (2010) conducted an evaluation of CCS for saltwater salmon aquaculture based on peer-reviewed material. They noted that the durability of any individual salmon farm will be dependent on its location, mooring, and how the floating structure responds to waves and currents. Chadwick et al. (2010) also noted that the type of material used for the CCS (especially whether it is flexible or solid-walled) and its shape will influence how the system responds to weather and ocean conditions**.**

The flexible or solid nature of the CCS may impact the risk of farmed fish escapes. SSAT (2019) notes that interactions with wildlife may be reduced with the use of solid-walled CCS compared to ONPS. While flexible-walled CCS may be more likely to tear or rupture due to harsh weather conditions or marine mammal interactions. To reduce the risk of fish escaping in the event of a tear or rupture of the CCS, Eriksson et al. (2017) suggested the addition of a net outside the CCS.

Lastly, mooring lines and anchoring systems may pose issues for marine mammals such as a risk of entanglement. Since marine CCS are water-based and require mooring and anchoring to keep them in place, SSAT (2019) noted that they would still have risks associated with marine mammal interactions in this way.

3.3.4 Environmental Impacts of CCS from a Life Cycle Perspective

Many of the previously discussed studies and reports (Haya, 2001; Hall-Spencer and Bamber, 2007; Cohen, 2012) address the impacts of ONPS salmon farms based on how they affect local ecosystems. Since CCS appears to alleviate many of these impacts (to an extent), it may be easy to lose sight of the larger global impacts (e.g., the global warming potential of CCS compared to ONPS). Using life cycle assessments (LCAs), as was done by Ayer and Tyedmers (2009) and McGrath et al. (2015), it may be possible to better determine the environmental impacts associated with CCS. These assessments take into consideration not just the farming process but the effects that may occur during the entire life cycle of the process (i.e., from the extraction of raw materials, manufacturing of various components, and transport to infrastructure setup and operation of the system).

Ayer and Tyedmers (2009)

Through an LCA, Ayer and Tyedmers (2009) found that replacing ONPS with semi-closed containment floating bags had a relatively small decrease in life cycle impacts associated with salmon aquaculture. The LCA focused on the following impact categories: abiotic depletion (ABD), global warming potential (GWP), human toxicity potential (HTP), marine toxicity potential (MTP), acidification (ACD), eutrophication (EUT), and cumulative energy demand (CED).

Ayer and Tyedmers (2009) did assessments based on the following two scenarios:

1. The ONPS would use fossil fuels to generate power (the conventional scenario) and the CCS systems would be connected to the hydroelectric grid.
2. The ONPS would use fossil fuels to generate power and the CCS systems would use a standardized Canadian electricity mix of 61% hydro, 18% coal, 13% nuclear, 4% oil, and 4% natural gas.

Figure 13, below, presents the life cycle contributions of the different aquaculture technologies assessed by Ayer and Tyedmers (2009) to the various environmental impact categories (ABD, GWP, HTP, MTP, ACD, EUT, and CED) based on the first scenario where all the CCS systems are connected to a hydroelectric grid and ONPS uses fossil fuels to generate electricity. In this scenario, the life cycle environmental impacts associated with the use of a floating bag CCS showed a marginal decrease (over ONPS) across all impact categories except CED.

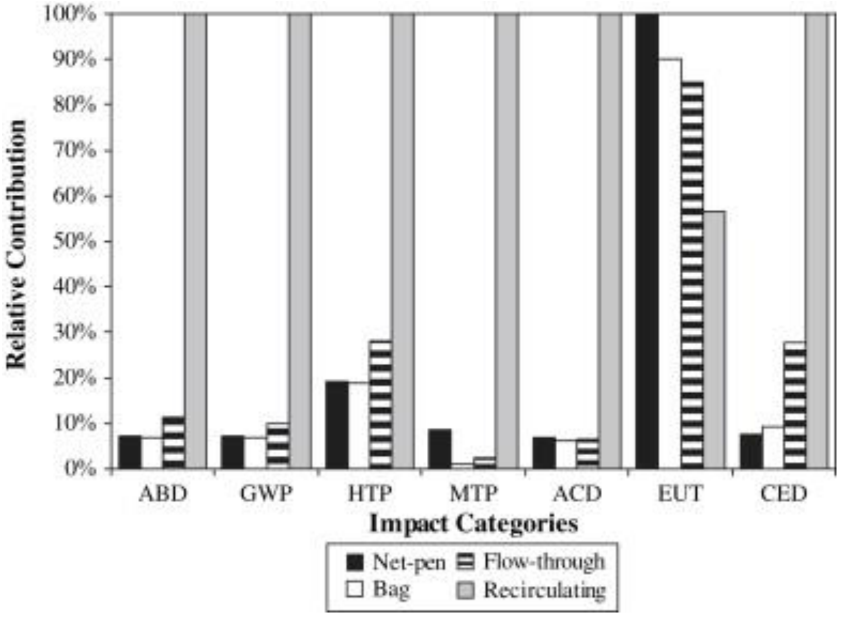


Figure 13. *Relative comparison of life cycle contributions to environmental impact categories for an open net pen system (ONPS), floating bag closed containment system (CCS), flow-through land-based CCS, and recirculating CCS, assuming all the CCS systems are connected to a hydroelectric grid and ONPS uses fossil fuels to generate electricity (Ayer and Tyedmers, 2009).*

Figure 14, below, presents the life cycle contributions of the different aquaculture technologies assessed by Ayer and Tyedmers (2009) to the various environmental impact categories (ABD, GWP, HTP, MTP, ACD, EUT, and CED) based on the second scenario where all the CCS systems operate on a standard Canadian electricity mix and ONPS uses fossil fuels to generate electricity. In this scenario, the life cycle impacts associated with the use of a floating bag CCS showed an increase (over ONPS) across all impact categories except MTP.

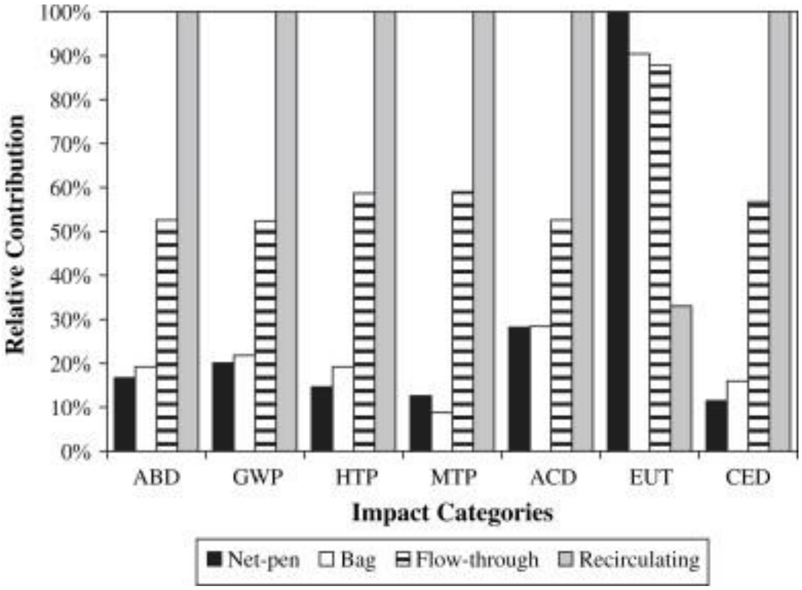


Figure 14. *Relative comparison of life cycle contributions to environmental impact categories for an open net pen system (ONPS), floating bag closed containment system (CCS), flow-through land-based CCS, and recirculating CCS, assuming all the CCS systems operate on a standard Canadian electricity mix and ONPS uses fossil fuels to generate electricity (Ayer and Tyedmers, 2009).*

In both scenarios (Figures 13 and 14), the CED for ONPS is less than that of all other closed containment technologies. Therefore, based on these assessments, Ayer and Tyedmers (2009) predict that energy demand for CCS will be more than that of ONPS, which is congruent with results from SSAT (2019).

The life cycle impact results for the floating bag CCS changed from a marginal decrease over ONPS (Figure 13) to greater than that of ONPS (Figure 14) when the source of energy for the CCS changed from hydroelectricity to a standard Canadian electricity mix. This indicates that the decrease in life cycle environmental impact when replacing ONPS with CCS may be dependent on the source of power used by the farm (Ayer and Tyedmers, 2009). This may suggest that in order for CCS to be environmentally beneficial over ONPS (from a life cycle perspective), a connection to British Columbia’s hydroelectric grid or another form of clean energy will be important.

It should be noted that Ayer and Tyedmers (2009) assumed that waste from the floating bag CCS was released back into the aquatic environment (without any treatment or collection). Therefore, this might be why their results showed that floating bag CCS only had a marginal decrease in life cycle impacts in the first scenario and had an increase in life cycle impacts in the second scenario. If the capture and treatment of wastewater were considered with the floating bag CCS, the life cycle impacts associated with this system may have been less. Although, energy requirements relating to wastewater capture and treatment could result in even higher energy demands for the floating bag CCS.

McGrath et al. (2015)

McGrath et al. (2015) conducted an LCA of a commercial solid-walled marine CCS deployed in British Columbia, using the following life cycle impact categories: global warming potential, acidification potential, marine eutrophication potential, cumulative energy use, and biotic resource use. The assessed CCS was connected to the hydroelectric grid, had a waste capture system to collect solids and semi-solids (which was dewatered and pumped to land to be composted), and used a fish feed consisting of 60% fish meal, 20% fish oil, and 20% wheat. The inventory models used by McGrath et al (2015) pertained to major subsystems within salmon production from cradle to farm-gate (e.g., on-site emissions, on-site energy use, feed production, smolt production, transportation, and infrastructure).

The results of this LCA indicated that feed production and on-site energy use contributed the most to global warming potential, acidification potential, biotic resource use, and cumulative energy use. However, these were mainly influenced by the inputs associated with feed production (e.g., raw materials used) and on-site energy (e.g., energy source). For the impact category of marine eutrophication potential, “on-site emissions of nutrients” was the subsystem that contributed most significantly (96.8%). These results lead to the conclusion that feed production, on-site energy, and on-site emission of nutrients should be key areas of focus when determining how to improve the life cycle environmental impacts of salmon farming in solid-walled marine CCS.

3.4 Social and Economic Impacts of Marine CCS Compared to ONPS

Literature involving the social and economic impacts of marine CCS compared to ONPS is further subdivided into the following sections: areas of significant costs for marine CCS;

improving the economic viability of marine CCS; local socio-economic impacts of replacing ONPS with marine CCS; and the environmental and social license associated with marine CCS.

3.3.1 Areas of Significant Costs for Marine CCS

The financial feasibility study by Boulet et al. (2010) indicated that capital costs associated with marine CCS would be more than that of ONPS. Although SSAT (2019) did not provide a cost comparison between marine CCS and ONPS, it stated that the capital cost of marine CCS could range from \$5 to \$15 per kg of salmon produced; this broad range was attributed to the wide variety of marine CCS designs that were being developed and evaluated. Eriksson et al (2017) acknowledged that these costs will likely decrease in the future as marine CCS technology become more established.

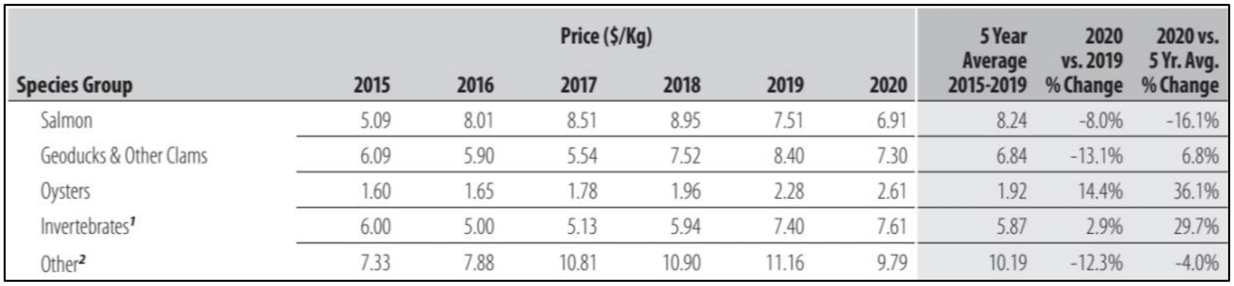
Trials of marine CCS have been conducted such as the pilot project by Mariculture Systems in the State of Washington. Mariculture Systems reported operating costs associated with their marine CCS to be lower than ONPS: \$1.7 million vs. \$1 million respectively (Weston, 2013). Mariculture Systems accounted for the lower operating costs (assessed on the basis of the weight of salmon produced) to aspects such as “reduced mortality, reduced feed costs..., [and] higher stocking densities” (Weston, 2013). This agrees with the contributions made by participants in the initial engagement process report for the ONPS transition plan in British Columbia (DFO, 2021), which stated that S-CCS could potentially be cost-competitive with ONPS as there may be cost savings associated with “lice problems, reducing fish mortality and achieving a higher feed conversion ratio”.

3.3.2 Improving the Economic Viability of Marine CCS

A way to improve the return on investment with salmon aquaculture is to increase the comparative number of fish produced (i.e., increase stocking densities) per pen so that more fish can be produced in a pen within a given amount of time (Weston, 2013; Eriksson et al., 2017). While increasing the stocking density of fish in CCS also increases the total amount of waste produced, the infrastructure specific to this type of fish culture allows for the collection of this waste so the environmental impact could still be kept low at higher stocking densities. Without compromising salmon welfare, it is possible to achieve stocking densities of 75kg/m^3 within marine CCS (Thorarensen and Farrell, 2011; Calabrese, 2017; Sveen et al., 2016). Conversely, ONPS are limited to salmon stocking densities below 22 kg/m^3 as densities above this threshold results in poor fish health (Turnbull et al., 2005).

Since higher stocking densities are possible in CCS without significant negative impacts on salmon welfare or the local environment, marine CCS may still be able to sustainably contribute to Canada’s gross domestic product. Because cultured salmon values have been decreasing since 2019 as shown in Table 3, the dependence on farms attaining higher stocking densities to make up for this declining product value may be a way of resolving this important issue.

Table 3. *Aquaculture farmgate values in $/kg for salmon and other aquatic species groups, British Columbia during 2015-2020 (AgriService BC 2022).*



	Price ($/Kg)								
Species Group	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**5 Year Average 2015-2019**	**2020 vs. 2019 % Change**	**2020 vs. 5 Yr. Avg. % Change**
Salmon	5.09	8.01	8.51	8.95	7.51	6.91	8.24	-8.0%	-16.1%
Geoducks & Other Clams	6.09	5.90	5.54	7.52	8.40	7.30	6.84	-13.1%	6.8%
Oysters	1.60	1.65	1.78	1.96	2.28	2.61	1.92	14.4%	36.1%
Invertebrates[1]	6.00	5.00	5.13	5.94	7.40	7.61	5.87	2.9%	29.7%
Other[2]	7.33	7.88	10.81	10.90	11.16	9.79	10.19	-12.3%	-4.0%

Price premiums may be possible for salmon farmed in CCS with good husbandry practices. For example, Mariculture Systems indicated a price premium of $0.50 per pound ($1.11 per kg) above ONPS-produced salmon (Marshall 2003). However, SSAT (2019) notes that these premiums could be lost once ONPS is phased out and new technology market share increases. Thus, price premiums may only contribute to the economic viability of CCS in the short term.

3.3.3 Local Socio-economic Impacts of Replacing ONPS with Marine CCS

According to SSAT (2019), if ONPS is replaced with marine CCS in British Columbia, the number of direct jobs associated with salmon farming may decline slightly, but this drop would be significantly less than what is predicted for replacement by an equivalent, but land-based, recirculating system. Since there are still location limitations with marine CCS (e.g., coastal aquatic environments with low currents), if replacement of ONPS occurs, the number of jobs currently in existence with the latter is predicted to remain the same in the coastal communities (SSAT, 2019). The main difference between marine ONPS and CCS is that job numbers may increase somewhat for the latter, and this is because the level of technological expertise that may be required with the CCS will be greater. Also, some technical salaries are expected to be somewhat higher with the replacement by CCS (SSAT, 2019).

3.3.4 The Environmental and Social License Associated with Marine CCS

A review of CCS technologies by Pendleton et al. (2005) indicated that the economic costs of the environmental impacts associated with each aquaculture system and the public's perceptions towards each system will need to be assessed (along with the capital and operational costs) to perform a more accurate costs comparison of the aquaculture systems.

By replacing ONPS with marine CCS, lower ecological impacts may be achieved such as a decrease in wild salmon sea lice infestations and less waste loading into the nearby aquatic environment (Nilsen et al., 2017; Eriksson et al., 2017). However, social perception towards marine CCS salmon farms may not be much better than ONPS as the systems are still in the aquatic environment. The environmental risks associated with the marine CCS, which may not be much less than that of ONPS if waste collection and hydroelectric grid connection are not employed (Ayer and Tyedmers, 2009), may still present a problem to some stakeholders.

Yip et al. (2017) conducted a primary research study comparing integrated multitrophic aquaculture (IMTA) to CCS aquaculture in terms of consumers' willingness-to-pay and their general perception of the seafood each system produced. The results showed that, while most of the people were willing to pay premiums for what may be deemed as sustainably farmed salmon, they preferred IMTA to CCS as they perceived the former to be more "natural".

Weston (2013) and Marshall (2003) both mention the importance of increasing consumer awareness of salmon production differences and possibly attaining product labels such as those provided by SeaChoice – a third-party organization that assesses the operations of Canadian seafood businesses and provides consumer product labelling based the businesses alignment with sustainability standards and criteria. Hence, product labelling may be important in making sustainably produced salmon more desirable, thereby increasing its value among consumers.

Chapter 4: Conclusions and Recommendations

Based on the literature reviewed, there are both environmental benefits and drawbacks associated with marine CCS. Marine CCS has the following environmental benefits over ONPS: lower risk of sea lice and disease transmission to wild salmon, less waste loading of the surrounding aquatic environment if waste collection methods are utilized, and lower risk of fish escapes (which may further be reduced if solid-walled marine CCS is used instead of flexible-walled marine CCS). Moreover, marine CCS has the following environmental drawbacks when compared to ONPSs: higher energy demand, and a possible increase in life cycle environmental impacts associated with parameters such as global warming potential and human toxicity potential if a clean energy source such as hydroelectricity is not used.

The welfare status of farmed salmon by marine CCS may be on par with, or sometimes better, than ONPS if water quality within the system can be maintained at healthy levels. One salmon welfare improvement of marine CCS over ONPS, which may be of particular importance, is its protection against sea lice infestations within the pen which yields more healthy fish at harvest and alleviates costs associated with sea lice treatments.

Compared to ONPS, marine CCS offers more influent water stability due to the deeper source of water. However, the enclosed nature of the system teamed with higher stocking densities may increase the chance of poor water quality within the system. Therefore, more extensive monitoring and mechanised adjustment techniques may be required to keep water quality in marine CCS within healthy ranges. These additional measures to maintain fish welfare within marine CCS may add to the operational costs of the system. Although, it is possible that these costs may be offset by the cost benefits associated with the lower environmental impacts of marine CCS compared to conventional ONPS (Weston, 2013).

The capital costs associated with marine CCS are more than that of ONPS (e.g., $1.7 million vs. $1 million as per Mariculture Systems' trial) (Weston, 2013). However, the ability to achieve higher stocking densities with marine CCS (75kg/m^3) as opposed to that of ONPS (below 22kg/m^3) may produce a better return on investments.

In terms of the socio-economic benefits of marine CCS over ONPS, the benefits are more so associated with the negative socio-economic impacts of ONPS phase-out in British Columbia. Most of the salmon aquaculture jobs that would be lost during the phase-out of ONPS can be kept if marine CCS were to replace the ONPS. Additionally, there is a chance of higher pay with some of the jobs associated with marine CCS are more training and technical expertise may be required for its operation.

To conclude, this literature review suggests that marine closed containment systems (CCS) may make salmon aquaculture a more sustainable industry in British Columbia when compared to the open net pen systems (ONPS) that are currently in place. But it is recommended that siting of marine CCS farms should consider hydroelectric grid connectivity and attempts should be made to utilize other clean energy sources such as solar and wind at the farm and in other areas of production such as fish feed processing so that dependence on fossil fuels is decreased as much as possible. This will better ensure that the life cycle environmental impacts associated with marine CCS may be kept lower than that of ONPS. Furthermore, to determine the commercial feasibility of CCS as an alternative to ONPS, more research specific to the type of structure, location, environmental requirements within the enclosure, and other variables of interest must be conducted over an extended period so that impacts and risks associated with the specific systems may be more accurately represented.

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Appendix 1– PRISMA 2020 Checklist

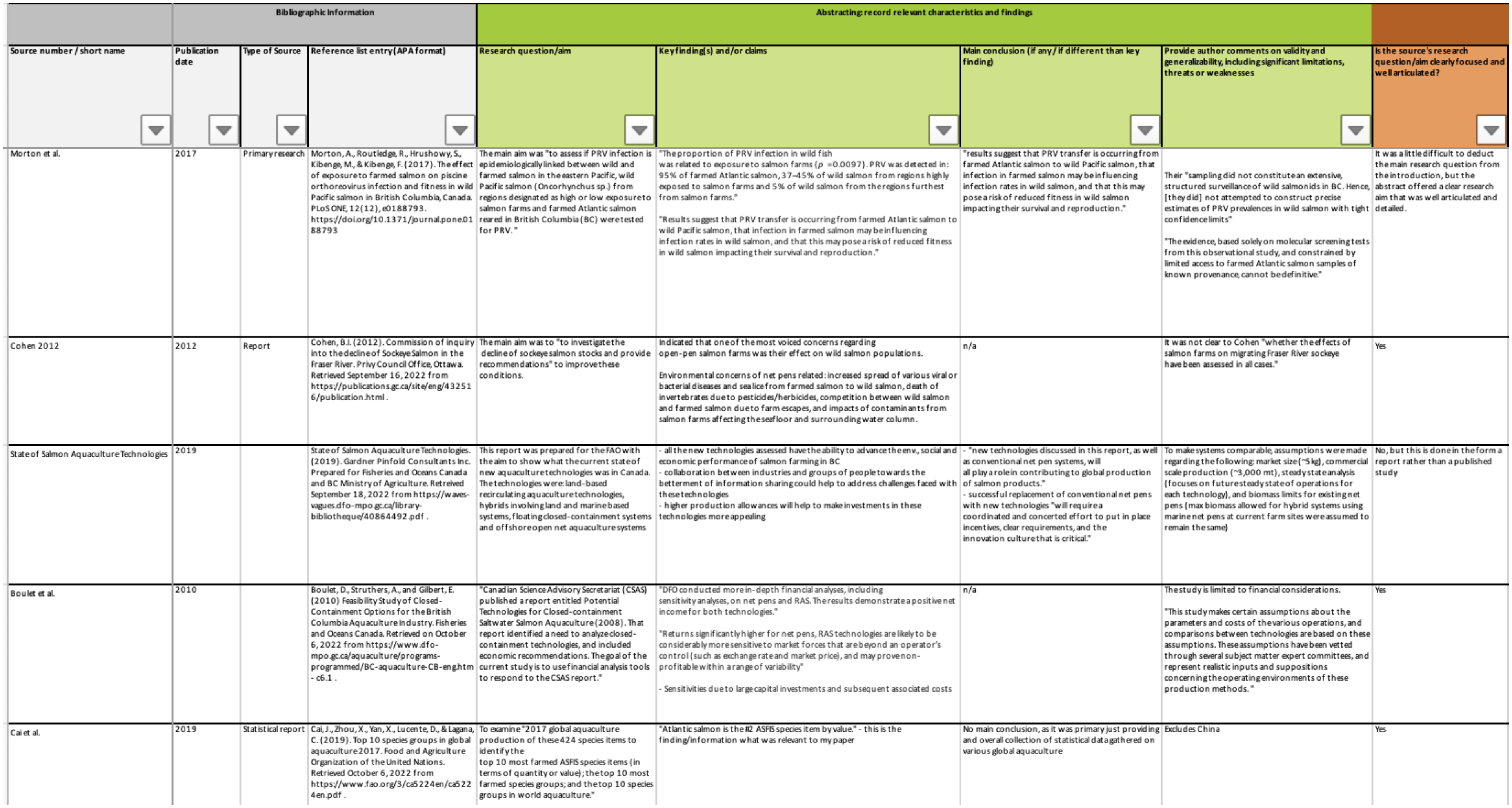
Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-	

Section and Topic	Item #	Checklist item	Location where item is reported
		regression).	
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	
Study characteristics	17	Cite each included study and present its characteristics.	
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	
	23b	Discuss any limitations of the evidence included in the review.	
	23c	Discuss any limitations of the review processes used.	
	23d	Discuss implications of the results for practice, policy, and future research.	
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	

Section and Topic	Item #	Checklist item	Location where item is reported
Competing interests	26	Declare any competing interests of review authors.	
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	

Appendix 2 – Literature Review Matrix

Please refer to the attached spreadsheet, Literature Review Matrix – 2022-12-14, for the complete matrix.



	Bibliographic Information			Abstracting: record relevant characteristics and findings				
Source number / short name	**Publication date**	**Type of Source**	**Reference list entry (APA format)**	**Research question/aim**	**Key finding(s) and/or claims**	**Main conclusion (if any / if different than key finding)**	**Provide author comments on validity and generalizability, including significant limitations, threats or weaknesses**	**Is the source's research question/aim clearly focused and well articulated?**
Morton et al.	2017	Primary research	Morton, A., Routledge, R., Hrushowy, S., Kibenge, M., & Kibenge, F. (2017). The effect of exposure to farmed salmon on piscine orthoreovirus infection and fitness in wild Pacific salmon in British Columbia, Canada. PLoS ONE, 12(12), e0188793. https://doi.org/10.1371/journal.pone.0188793	The main aim was "to assess if PRV infection is epidemiologically linked between wild and farmed salmon in the eastern Pacific, wild Pacific salmon (Oncorhynchus sp.) from regions designated as high or low exposure to salmon farms and farmed Atlantic salmon reared in British Columbia (BC) were tested for PRV."	"The proportion of PRV infection in wild fish was related to exposure to salmon farms (p =0.0097). PRV was detected in: 95% of farmed Atlantic salmon, 37–45% of wild salmon from regions highly exposed to salmon farms and 5% of wild salmon from the regions furthest from salmon farms." "Results suggest that PRV transfer is occurring from farmed Atlantic salmon to wild Pacific salmon, that infection in farmed salmon may be influencing infection rates in wild salmon, and that this may pose a risk of reduced fitness in wild salmon impacting their survival and reproduction."	"results suggest that PRV transfer is occurring from farmed Atlantic salmon to wild Pacific salmon, that infection in farmed salmon may be influencing infection rates in wild salmon, and that this may pose a risk of reduced fitness in wild salmon impacting their survival and reproduction."	Their "sampling did not constitute an extensive, structured surveillance of wild salmonids in BC. Hence, [they did] not attempted to construct precise estimates of PRV prevalences in wild salmon with tight confidence limits" "The evidence, based solely on molecular screening tests from this observational study, and constrained by limited access to farmed Atlantic salmon samples of known provenance, cannot be definitive."	It was a little difficult to deduct the main research question from the introduction, but the abstract offered a clear research aim that was well articulated and detailed.
Cohen 2012	2012	Report	Cohen, B.I. (2012). Commission of inquiry into the decline of Sockeye Salmon in the Fraser River. Privy Council Office, Ottawa. Retrieved September 16, 2022 from https://publications.gc.ca/site/eng/432516/publication.html .	The main aim was to "to investigate the decline of sockeye salmon stocks and provide recommendations" to improve these conditions.	Indicated that one of the most voiced concerns regarding open-pen salmon farms was their effect on wild salmon populations. Environmental concerns of net pens related: increased spread of various viral or bacterial diseases and sea lice from farmed salmon to wild salmon, death of invertebrates due to pesticides/herbicides, competition between wild salmon and farmed salmon due to farm escapes, and impacts of contaminants from salmon farms affecting the seafloor and surrounding water column.	n/a	It was not clear to Cohen "whether the effects of salmon farms on migrating Fraser River sockeye have been assessed in all cases."	Yes
State of Salmon Aquaculture Technologies	2019		State of Salmon Aquaculture Technologies. (2019). Gardner Pinfold Consultants Inc. Prepared for Fisheries and Oceans Canada and BC Ministry of Agriculture. Retreived September 18, 2022 from https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40864492.pdf .	This report was prepared for the FAO with the aim to show what the current state of new aquaculture technologies was in Canada. The technologies were: land-based recirculating aquaculture technologies, hybrids involving land and marine based systems, floating closed-containment systems and offshore open net aquaculture systems	- all the new technologies assessed have the ability to advance the env., social and economic performance of salmon farming in BC - collaboration between industries and groups of people towards the betterment of information sharing could help to address challenges faced with these technologies - higher production allowances will help to make investments in these technologies more appealing	- "new technologies discussed in this report, as well as conventional net pen systems, will all play a role in contributing to global production of salmon products." - successful replacement of conventional net pens with new technologies "will require a coordinated and concerted effort to put in place incentives, clear requirements, and the innovation culture that is critical."	To make systems comparable, assumptions were made regarding the following: market size (~5 kg), commercial scale production (~3,000 mt), steady state analysis (focuses on future steady state of operations for each technology), and biomass limits for existing net pens (max biomass allowed for hybrid systems using marine net pens at current farm sites were assumed to remain the same)	No, but this is done in the form a report rather than a published study
Boulet et al.	2010		Boulet, D., Struthers, A., and Gilbert, E. (2010) Feasibility Study of Closed-Containment Options for the British Columbia Aquaculture Industry. Fisheries and Oceans Canada. Retrieved on October 6, 2022 from https://www.dfo-mpo.gc.ca/aquaculture/programs-programmed/BC-aquaculture-CB-eng.htm - c6.1 .	"Canadian Science Advisory Secretariat (CSAS) published a report entitled Potential Technologies for Closed-containment Saltwater Salmon Aquaculture (2008). That report identified a need to analyze closed-containment technologies, and included economic recommendations. The goal of the current study is to use financial analysis tools to respond to the CSAS report."	"DFO conducted more in-depth financial analyses, including sensitivity analyses, on net pens and RAS. The results demonstrate a positive net income for both technologies." "Returns significantly higher for net pens, RAS technologies are likely to be considerably more sensitive to market forces that are beyond an operator's control (such as exchange rate and market price), and may prove non-profitable within a range of variability" - Sensitivities due to large capital investments and subsequent associated costs	n/a	The study is limited to financial considerations. "This study makes certain assumptions about the parameters and costs of the various operations, and comparisons between technologies are based on these assumptions. These assumptions have been vetted through several subject matter expert committees, and represent realistic inputs and suppositions concerning the operating environments of these production methods. "	Yes
Cai et al.	2019	Statistical report	Cai, J., Zhou, X., Yan, X., Lucente, D., & Lagana, C. (2019). Top 10 species groups in global aquaculture 2017. Food and Agriculture Organization of the United Nations. Retrieved October 6, 2022 from https://www.fao.org/3/ca5224en/ca5224en.pdf .	To examine "2017 global aquaculture production of these 424 species items to identify the top 10 most farmed ASFIS species items (in terms of quantity or value); the top 10 most farmed species groups; and the top 10 species groups in world aquaculture."	"Atlantic salmon is the #2 ASFIS species item by value." - this is the finding/information what was relevant to my paper	No main conclusion, as it was primary just providing and overall collection of statistical data gathered on various global aquaculture	Excludes China	Yes