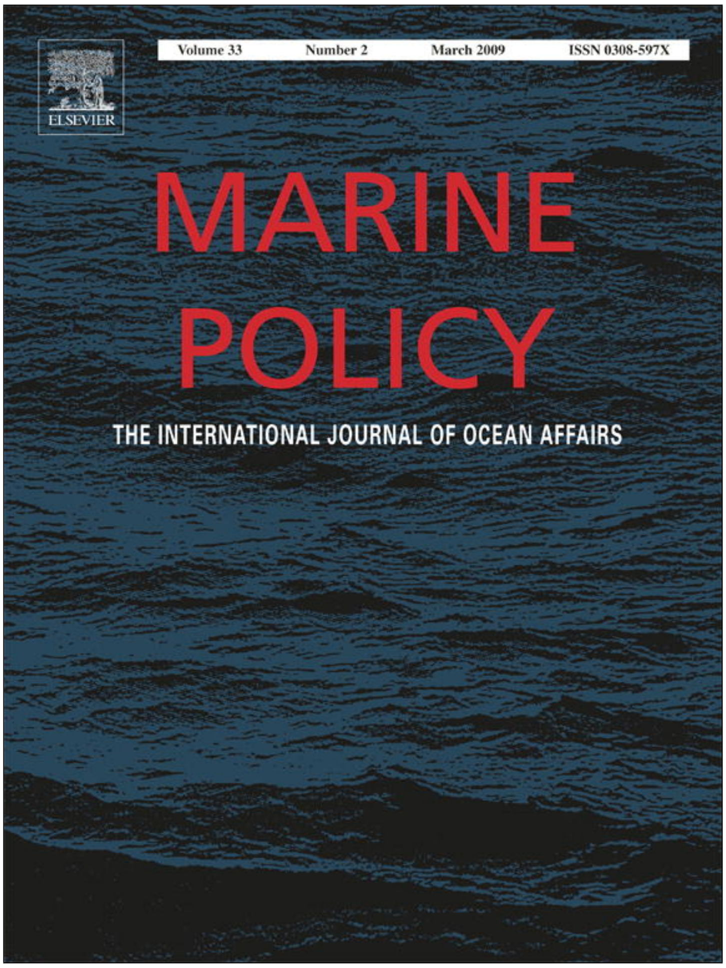
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Occupational health and safety hazards in Atlantic Canadian aquaculture: Laying the groundwork for prevention

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ABSTRACT

The growing aquaculture industry is projected to feature ever more prominently in the lives and economies of rural coastal communities in Atlantic Canada and around the world. Both private industry and government have a responsibility to ensure employment opportunities created in aquaculture take place in healthy, safe environments. However, systematic occupational health and safety (OHS) research within this industry, an important prevention tool, is still in its infancy. With particular emphasis on marine aquaculture in Atlantic Canada, we provide a detailed outline of the structure of the industry from feed production through to processing, identify potential OHS hazards associated with each of these activities and make recommendations for future research and action.

1. Introduction

Employment opportunities in the Atlantic Canadian fisheries industry have declined substantially since the early 1990s [1,2]. In contrast, the aquaculture industry has grown considerably during this period, representing a significant component of economic diversification in the region. Aquaculture, the cultivation of aquatic organisms, has developed into a commercial endeavor responsible for nearly half of all food fish production, globally [3]. Atlantic Canadian aquaculture production has grown four fold over the past 15 years [4], and represents approximately 10% of the food fisheries tonnage produced in the region [4,5]. With great expectations for future growth and employment within both global and Atlantic Canadian contexts, the aquaculture industry will play an increasing role in the socioeconomic fabric of coastal communities as well as in the occupational health of coastal workers.

In Canada, as elsewhere, workers, employers and other stakeholders (including contractors, engineers and equipment designers) associated with this rapidly expanding industry have a collective responsibility to protect the health, safety and well-being of individuals working within it. Specifically, the foundation of occupational health and safety (OHS) legislation in industrialized nations is the internal responsibility system. The internal responsibility system allocates a share of the responsibility for creating safe workplaces to each of these groups [6]. Workers, for example, have some responsibility for their personal safety and that of others. They also have the right to know about workplace hazards, the right to participate in workplace safety and the right to refuse unsafe work. Employers, managers and supervisors are responsible for playing a lead role in creating the workplace design and OHS procedures and structures required to attain safe workplaces [6]. The effective functioning of the internal responsibility system is monitored and supported by those involved in enforcement, compensation and prevention; otherwise termed, the external responsibility system. Accurate and timely information on hazards and the best methods to eliminate or reduce those hazards is a fundamental requirement of this approach to OHS.

Marine aquaculture is a complex industry that is composed of multiple facets. Primary prevention, through designing out potential risks, is the most effective way to protect occupational health and safety (OHS) and is crucially important in a relatively new, expanding and potentially hazardous industry. Secondary and tertiary prevention are also important. All three require active, hazard research, hazard assessment, monitoring of near-misses, injuries and occupational diseases, as well as attention to social and other factors mediating risk such as education, training, regulatory oversight and intervention, compensation and reporting [7]. Unfortunately, research on OHS in this industry is fragmentary and extremely limited at all levels. As a result, we have not been able to find a comprehensive list of hazards across the industry at regional, national or global levels. Here we provide a detailed outline of the structure of the industry from feed production through to processing, identify potential OHS hazards

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associated with each of these areas, and make some general recommendations for future research and action related to the industry. We place particular emphasis on work components and OHS hazards relevant to commercial, marine aquaculture in Atlantic Canada and comparable aquaculture industries around the world.

2. Methods

We investigated aquaculture production processes and the existing knowledge relating to occupational health and safety within the industry using a variety of information sources including peer-reviewed articles, governmental and non-governmental reports, books, professional society publications, online resources and personal observations or communications made directly by the authors. Peer-reviewed articles were searched using material safety databases maintained by the Canadian Centre for Occupational Health and Safety, PubMed/Medline, ISI Web of Knowledge, CSA Illumina and Google Scholar. Desired resources were organized bibliographically using Reference Manager 11.1 (Thomson Reuters Corp., Carlsbad, USA). Members of a project advisory committee consisting of OHS inspectors, educators, and industry association representatives from Atlantic Canada were also consulted on an earlier draft of this paper, providing useful insights and recommendations for research and knowledge transfer to the regional industry.

3. Aquaculture production systems

Canada's East Coast is dominated by the culture of salmonids, mainly Atlantic salmon (*Salmo salar*), blue mussels (*Mytilus edulis*) and eastern oysters (*Crassostrea virginica*), with various other finfish and shellfish species undergoing small-scale production and/or research and development ([4]; Table 1). Thus Atlantic Canada, like much of the global aquaculture industry, is composed of two main sectors; finfish and shellfish production. As a prelude to exploring the potential OHS hazards associated with Atlantic Canadian aquaculture, this section describes the major production phases and related activities associated with finfish and shellfish culture.

3.1. Hatchery production processes

Hatchery production is the most critical phase in finfish aquaculture. High investments are required to produce juvenile fish that are then typically relocated and grown to market size. The hatchery cycle consists of spawning broodstock, egg incubation, early larval development and the production of healthy juveniles for further growth [8]. Hatcheries consist of land-based flow-through or recirculation systems, where water is pumped to a series of incubators and/or tanks, of diverse sizes and shapes, which may serve various purposes ranging from live feed production to the rearing of the cultured species itself. The major task of hatchery workers involves ensuring the cultured species is

Table 1
Predominant and notable alternative species under development for Atlantic Canadian aquaculture and the culture techniques applied

Cultured species	Culture techniques		
	Hatchery phase	Nursery phase	Grow-out phase
Predominant species			
Finfish			
Atlantic salmon (*Salmo salar*)	Broodstock; land-based facilities	N/A	Predominately ocean net pen
Rainbow trout (*Oncorhynchus mykiss*)	Broodstock; land-based facilities	N/A	Predominately ocean net pen
Shellfish			
Blue mussels (*Mytilus edulis*)	Wild settlement upon pelagic systems	Pelagic long-line system	Pelagic long-line system
Eastern oysters (*Crassostrea gigas*)	Land-based broodstock or wild caught pelagic system	Pelagic and benthic culture systems	Pelagic and benthic culture systems
Sea scallops (*Placopecten magellanicus*)	Land-based broodstock or wild caught pelagic system	Pelagic long-line system	Pelagic long-line system
Alternative species			
Finfish			
Atlantic cod (*Gadus morhua*)	Broodstock; land-based facilities	N/A	Predominately ocean net pen
Haddock (*Melanogrammus aeglefinus*)	Broodstock; land-based facilities	N/A	Predominately ocean net pen
Halibut (*Hippoglossus hippoglossus*)	Broodstock; land-based facilities	N/A	Predominately ocean net pen
Arctic charr (*Salvelinus alpinus*)	Broodstock; land-based facilities	N/A	Ocean net pen and land-based facilities
American eel (*Anguilla rostrata*)	Wild-caught juveniles		Land-based facilities
Brook charr (*Salvelinus fontinalis*)	Broodstock; land-based facilities	N/A	Ocean net pen and land-based facilities
Spotted wolfish (*Anarhichas minor*)	Broodstock; land-based facilities	N/A	Land-based facilities
Atlantic sturgeon (*Acipenser oxyrhynchus*)	Broodstock; land-based facilities	N/A	Land-based facilities
Shortnose sturgeon (*Acipenser brevirostrum*)	Broodstock; land-based facilities	N/A	Land-based facilities
Bluefin tuna (*Thunnus thynnus*)	Wild-caught juveniles	N/A	Ocean net pen
Tilapia (*Oreochromis* spp.)	Broodstock; land-based facilities	N/A	Land-based facilities
Shellfish			
Sea urchin (*Strongylocentrotus droebachiensis*)	Land-based broodstock or wild caught benthic system	Land-based facilities or benthic culture systems	Land-based facilities; benthic culture systems or ranching
Quahaugs (*Mercenaria mercenaria*)	Land-based broodstock or wild caught benthic system	Land-based facilities or benthic culture systems	Benthic culture systems
Soft-shell clams (*Mya arenaria*)	Land-based broodstock or wild caught benthic system	Land-based facilities or benthic culture systems	Benthic culture systems
Red abalone (*Haliotis rufescens*)	Land-based broodstock or wild caught benthic system	Land-based facilities	Land-based facilities

receiving an optimal supply of feed. For salmonids, commercial dry feeds are used throughout their life cycle. However, for most marine finfish such as Atlantic cod (*Gadus morhua*), live feed is necessary during larval development requiring hatcheries for these species to also incorporate laborious algal and invertebrate production systems [8]. Other tasks include monitoring water quality and the health of the fish; moving, grading and counting the fish; and the overall maintenance of the facility.

Shellfish hatcheries are few and far between in Atlantic Canada, largely because of high operational costs and an industry dominated by mussel production. Mussel production relies on natural collection, where larvae settle on vertically suspended rope and are graded prior to being transferred to grow-out sites [8]. The increasingly popular culture of the eastern oyster has, to date, also relied on natural collection methods, where a substrate is placed near oyster beds to collect settling larvae, similar to that employed for mussel culture. However, natural oyster production is quite temporally variable, making hatchery production attractive under a suitable economic climate.

Oyster hatcheries are common components of eastern oyster production in the United States and in Pacific oyster (*Crassostrea gigas*) aquaculture on the northwest coast of North America. Such hatcheries require facilities to produce algae for feed, condition and spawn broodstock, rear and settle larvae on a substrate, and grow the juveniles to an acceptable size for transfer to the grow-out phase [8,9].

The major tasks of shellfish hatchery workers are similar to those described for finfish hatcheries. The basic design and components of shellfish hatcheries are also similar to those for finfish, with the exception of the nursery system. Nursery systems are the final stage in hatchery produced shellfish, where juveniles are reared immediately prior to grow-out. They function to reduce the labour required to produce the algae within the hatchery. They are typically located outdoors and use a series of land-based ponds/tanks close to shore or on floating rafts located in well-protected, productive seawater environments such as an estuary or lagoon [8,9]. All systems are engineered to ensure a continuous supply of algal-rich water is pumped past the cultured species in an upwelling fashion. Nursery systems for wild caught juveniles, like those most commonly used in Atlantic Canada, are similar to grow-out systems and are discussed in the following section.

3.2. Grow-out production processes

Atlantic Canadian finfish grow-out operations consist of marine net pen and land-based operations. Land-based recirculation or flow-through systems are similar to hatchery operations. Net pen or cage culture operations are characterized by floating mesh structures typically located in sheltered, near shore environments with desirable temperature and water exchange regimes [8,10,11].

Grow out operations consist of multiple net pens that are anchored to the ocean floor and sometimes linked together with a walking platform for easy employee access. More common in Atlantic Canada, however, are floating, circular plastic cages accessed using small vessels. These small vessels are used for transportation as well as various farm tasks. As in hatcheries, major worker tasks include feeding, monitoring water quality and fish health, and maintaining the physical structure of the operation. Finfish are fed artificial pellets numerous times daily either by hand or using semi-automated feed blowers. The blowers allow reduced physical effort and increase the evenness of feed delivery, an important technique for increasing feed access to all competing farmed fish. Below surface monitoring of the physical structure, fish health and mortality removal involve SCUBA certified employees or contractors who regularly dive, inspect and perform other required tasks while submerged. Cage sites located in near-shore waters that freeze at the surface require employees to traverse the ice to monitor the cages. Site set-up and harvest requires the services of a larger, boom mounted vessel that is capable of towing the floating cages to and from shore and carrying a large amount of fish upon slaughter. The slaughter process typically involves shocking the fasted fish with a high respiratory exposure to gaseous carbon dioxide [12] and severing the major blood vessels leading to the gills prior to storage in an icy slurry [10].

A notable supplementary commercial development triggered by finfish grow-out operations is net servicing. In these operations, specialist companies offer various net services to growers that may include cage mesh repairs, washing, disinfection, anti-foulant application and off-season storage [13]. Anti-fouling compounds prevent algae and mollusc species from settling on the surface of the cage nets. Anti-foulant can be applied by spray or dip methods. Increasingly, service companies possess purpose-built application machines that dip the net into the anti-fouling agent prior to it being air-dried. Approved anti-fouling compounds are copper-based solutions. These are considered to be a potential environmental contaminant [14,15].

Shellfish grow-out systems used in Atlantic Canada are far more diverse than those employed in the finfish industry. In addition to land-based facilities, there are marine benthic and pelagic culture systems that are most commonly located near the shore [8]. Our discussion will focus on methods pertaining to the more commonly cultured bivalves in Atlantic Canada including mussels (*Mytilus edulis*), oysters (*Crassostrea virginica*), scallops (*Placopecten magellanicus*), and clams (*Mercenaria mercenaria, Mya arenaria*). Benthic culture systems refer to grow-out operations where animals are housed on or near the ocean floor [8,16]. These systems are commonly used for oyster and clam grow-out production in intertidal zones, where the farmed animals are uncovered from seawater at low tide. Employee tasks include preparing the intertidal farming grounds by clearing, plowing and marking the area. Culture containers are anchored to the sediment, where they are monitored periodically for maintenance and assessment of animal health, growth, quality and survival.

Pelagic culture systems include operations where animals are suspended from the ocean surface. These systems are commonly used for mussel, oyster and scallop grow-out production as well as nursery rearing for oysters and clams. Pelagic culture in Canada consists of variants of the long line system, where plastic rope is floated near the surface with buoys and anchored to the sea floor [8,16]. Variants include surface-floating and below-surface suspension designs. Surface-floating systems feature plastic mesh bag or cage culture containers that attach to the long line and remain near the surface to take advantage of the higher water temperatures, which increase growth. These systems are used to culture oysters and clams, commonly during a nursery stage prior to bottom culture transfer. Below surface suspension systems may feature bag, cage, as well as mesh tube, tray or lantern/pearl nets that are attached to a rope and hung vertically from the long line. These systems are used to culture mussels, oysters and scallops. Employee tasks include periodic maintenance and assessment of animal health, growth, quality and survival. Pelagic systems require such duties to occur from vessel platforms that typically possess a winch and boom feature for manipulating culture containers and socking/grading/declumping machinery. Winter harvests can occur in ice-covered bays, where workers cut through the ice with a chainsaw and pull the long line onto the ice surface using a winch. Diving is frequently required for a variety of tasks, including during winter harvests.

There is increasing interest in developing aquaculture technologies that will allow grow-out operations to take place further offshore in order to reduce space limitations as well as address aesthetic and environmental concerns. Adapting cost-effective cage grow-out systems to function in a dynamic and often dangerous offshore environment is a technically demanding engineering assignment. A number of offshore finfish cage designs are currently under research and development including surface, partly submerged and submerged designs varying in mechanical flexibility [17]. The commercial application of some of these technologies has been attempted in various regions of the world with some level of success [17,18]. Similarly, considerable efforts are underway in the United States to develop submersible long-line mussel culture and sea scallop suspension systems that are suitable for offshore deployment [19]. Little information is available on the projected job tasks and working conditions associated with these advanced culture systems. However, these operations will likely require platforms with space for living quarters, feed and equipment storage, administrative and maintenance facilities, laboratories for monitoring health and water quality and helicopter landing pads for transportation. Purpose-built industry support vessels or fixed platforms similar to those used in offshore oil and gas are potential sources for such space [17]. Diving tasks are recognized as being very dangerous in this environment, thus robotic solutions are under development [18].

3.3. *Processing production processes*

Processing is the final stage in aquaculture production. During processing the cultured animals are prepared for market. From the point of view of work tasks and technologies, this stage differs little from that found in more traditional forms of wild seafood processing [20–22] and sometimes takes place in the same facilities. Primary processing plants used in aquaculture are on-shore facilities that are typically characterized by long preparation tables and some form of mechanized sorting and/or gutting and, in finfish, filleting machinery. Plant worker tasks involve machine operation, cleaning, portioning, packaging and storing of the food product for shipment and plant maintenance. Many facilities are also equipped for secondary processing activities such as cooking, canning, smoking, freezing or drying. Despite the overlap and similarities, aquaculture processing can differ from traditional seafood processing in terms of season length, automation and standardization of production.

3.4. *Feed manufacturing production processes*

Juvenile and adult finfish are fed a dry, extruded pellet that is specifically designed to provide producers with a nutritional, user-friendly diet for their animals. Access to quality feed is crucial to the finfish industry and accounts for the single greatest cost of production [23]. The finfish aquaculture feed manufacturing process utilizes the same technologies that are involved in the making of land-based livestock and pet feeds. These technologies form a highly specialized and highly mechanized process that consists of grinding, mixing and pellet formation [23]. The grinding mill reduces the size of the primary ingredients, such as grain mill by-products, animal by-products and soybean meal, by either forcing them through a screen or by a cutting action. Following grinding, the ingredients are mixed together carefully either manually with a shovel or, more commonly, they are mechanically mixed using a rotating auger or paddle wheel. The feed mixture then enters the pellet mill where it is first moistened with steam, compressed, extruded through a die and then cut to the desired size. The pellets are graded, cooled and dried by means of a perforated conveyor belt or vertical hopper before being packaged for sale. Feed mill employee responsibilities include the operation and maintenance of the equipment as well as the receiving, storing, packaging and shipping of ingredients and/or feed produced.

4. OHS hazards in finfish and shellfish aquaculture

Aquaculture consists of many diverse, labour intensive occupational tasks involving a complex variety of machinery, equipment, chemicals, biological agents and sometimes challenging physical environments. Surprisingly, there have been few attempts to detail the health and safety issues associated with this growing industry and none of the existing research has focused on the Canadian industry [24–27]. Moreover, our efforts to gather aquaculture workers' injury claims statistics for Canada's four Atlantic provinces and Quebec revealed some provinces were unable to provide information while others had fairly detailed claims information on hand.

The following section draws on existing OHS research, proprietary standard operating procedures (SOPs) and the overview of work processes in different parts of the industry outlined above, to explore the real and potential hazards associated with finfish and shellfish aquaculture in Atlantic Canada and elsewhere. Our exploration suggests that elements of all of the broad OHS hazard categories including work design, physical, chemical, biological and psychosocial hazards are likely present in the industry ([28]; Fig. 1).

4.1. *Work design hazards*

Poorly designed workplaces and workstations that require heavy lifting, prolonged standing, awkward postures and repetitive work are associated with a high risk of various work-related musculoskeletal disorders (WMSDs). These disorders can affect both upper and lower limbs. They include, among others, low back pain, neck and shoulder pain, bursitis, tendonitis, tenosynovitis and carpel tunnel syndrome. The workplace environments and production processes associated with all of the phases of both fish and shellfish aquaculture are likely to include some or all of the

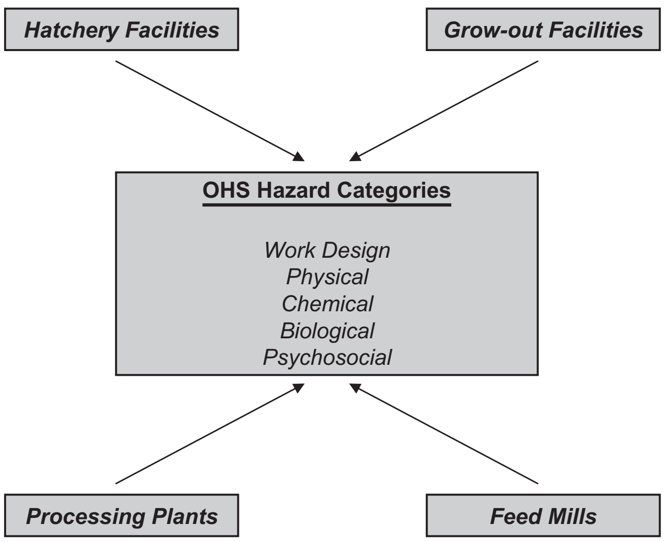

Fig. 1. Aquaculture industry phases linked with the major occupational health and safety (OHS) hazard categories. Hazards within each category require identification, evaluation and management solutions as they apply to all phases of the industry.

above-noted work design hazards. Unfortunately, there is little research on this aspect of hatchery or grow-out operations. Mitchell (2001) examined the ergonomic issues associated with Australian pearl oyster (*Pinctada* spp.) grow-out operations, which utilize pelagic grow-out technologies similar to those in Atlantic Canada [29]. The study found that these workers experienced a high risk of musculoskeletal injury when pulling long-lines on board vessels due to heavy loads and repetitive, over-extended lifting postures. In Atlantic Canada, hatchery and grow-out operations can also require employees to move around heavy bags of feed, heavy netting and engage in long periods of tiresome, repetitive hand feeding. There is some evidence of awareness of these work design hazards in aquaculture in some jurisdictions and in companies where basic health and safety guidelines for aquaculture have been implemented [25,30,31]. However, we found no published attempts to quantify musculoskeletal symptoms among workers involved in these phases of the industry, a potentially valuable tool for assessing the appropriateness of existing health and safety guidelines and broadening access to information.

A growing number of studies have examined the risk of WMSDs in seafood processing but very few have focused explicitly on the aquaculture industry. Seafood processing studies are relevant to our understanding of risk because of strong similarities in the work and technologies involved, although there are likely differences in hours of exposure, season length, the speed of work, repetition and in levels of automation within and between these types of processing operations. Many processing jobs involve repetitive and vigorous motions, extended periods of time standing, heavy lifting and awkward postures. A fast paced environment is also typical of the industry [21,32,33]. Musculoskeletal disorders affecting the neck, shoulders, back and upper and lower limbs with disorder prevalence and severity correlated with particular worker tasks have been documented [34–36]. Claims for soft tissue injuries can be common in seafood processing and there is some evidence of under-reporting linked to employment uncertainty and seasonality [37]. Due to the gender-division of labour, women workers may be more at risk of disorders caused by repetitive motions in seafood processing, whereas men are more exposed to disorders related to heavy lifting [38–41].

4.2. *Physical hazards*

Physical hazards to occupational health that are found in most industrial processes include those associated with slips and trips, falls from height, workplace transportation, dangerous machinery, electricity and fire safety, and exposure to heavy metals. With the exception of heavy metals, all of these hazards are likely to be found in many of the work environments in aquaculture. Physical agents associated with risk include noise, vibration, heat and cold stress and lighting. All of these, with perhaps the exception of vibration, can be found within the broader industry.

4.3. *Slips, trips and falls from height*

The agents for slips and trips potentially associated with all of the stages of aquaculture production would include wet, slippery and in some cases icy surfaces, cluttered work environments, open gutters and outside and cold storage work environments. Falls from height might be associated with construction and repair of aquaculture operations as well as with some of the production processes such as feed storage or hatchery head tank maintenance.

4.4. *Workplace transportation and trucking*

Motorized transportation is integral to any modern aquaculture operation. Aquaculture operations may involve the use of small boats, larger boats with booms, cars, trucks, ATV's, snowmobiles and forklifts. In the existing literature, the most commonly cited risks are those associated with the operation of small boats in grow-out operations. These small boats are used for a variety of general tasks that include transportation, grading/harvesting and feeding. In the British Columbia fishing industry, it is estimated that 86% of job-related fatalities, between 1991 and 2001, were due to drowning from falls from a vessel platform [42]. While the risk of hazardous ocean conditions is far less severe at predominantly near-shore aquaculture grow-out locations than in the open sea, precautionary efforts such as wearing personal flotation devices, ensuring equipment is well maintained, that employees are mindful of weather conditions and that employees are well versed in other operational protocols are critical [25]. Well designed operational protocols also help to ensure limbs are clear from an operating winch drum, outboard motors steer clear from lines and mesh near the surface, and the vessel platform is kept tidy to avoid trip hazards [30].

Safety regulations and concerns associated with land-based vehicles such as trucks and ATVs are also relevant to the aquaculture industry. Trucking between different phases of the operation is a widespread requirement in much of the industry. The use of trucks and ATVs on sea ice during shellfish harvests or during finfish cage inspections also deserves mention. Weight-induced ice break up is an obvious drowning and cold water exposure hazard. Safe use on ice requires the best available local knowledge of ice thickness prior to undertaking such activities.

Forklifts and other lifting industrial vehicles are commonly used to transport loads of heavy goods, be it feed in feed mills, skids of fish and shellfish, or packaged product. These loads are transported into and between processing and cold storage areas and onto and off of trucks and boats. The physical hazards involving forklifts in the workplace are well documented with most injuries caused by collisions with pedestrians and improper lifting procedures resulting in material falling and striking the driver or surrounding workers [43]. An additional risk in the aquaculture industry relates to the use of forklifts on wharves where forklifts can tumble into the water and drop material onto vessel decks, and where frequent public access means attention needs to be paid to outside visitors wandering through the work area.

4.5. *Dangerous machinery*

Aquaculture operations frequently require a range of other potentially dangerous machines. Handling knives and working with processing, grading or feed manufacturing machines can lead to injuries such as cuts, sprains, broken bones, amputation and in the most extreme situations, death due to entrapment and crushing. Workers using or maintaining such machinery and working around conveyor belts need to be appropriately trained. Machinery with moving parts must be appropriately guarded and provisioned with accessible emergency stop buttons. Lockout/tagout procedures are required during maintenance of such machines.

4.6. *Electrical and fire safety*

Electrical and fire hazards exist in nearly all workplace environments and are a widely acknowledged safety concern. There are a few features of the aquaculture industry that have the potential to enhance the risks associated with electrical equipment and fires. First, in aquaculture, powered machinery is commonly used in close proximity to water or in wet/humid conditions increasing the risk of shock and electrocution should exposures occur. Second, aquaculture operations are often located far from fire fighting services and therefore, there is an increased risk of uncontrolled disasters. Third, land-based hatchery and grow-out operations commonly utilize ozone and oxygen gas to help manage water quality. Ozone is toxic if inhaled and inhalation causes serious respiratory and skin irritation. It is also a highly unstable explosion hazard in combustive situations [44]. Pure oxygen gas is also a severe fire hazard that may, in addition, lead to hyperoxia following prolonged exposure [45]. Gas cylinder handling and safety require procedural training. These rather high electrical and fire risk factors enhance the need for employers to minimize these risks and ensure aquaculture industry workers dealing with these hazards are appropriately trained.

4.7. Extreme temperature hazards

In the Atlantic Canadian industry, a substantial number of aquaculture workers are at risk of exposure to air and water temperatures that are near or below freezing, particularly during the winter months. Cold exposures would be particularly common for outdoor activities at hatchery and grow-out operations but can also occur in processing plants and feed mills. Prolonged exposure to extreme cold without proper thermal protection may result in frost nip, frost bite, or, in extreme cases, hypothermia [25,30,42]. Moreover, musculoskeletal disorders, such as those discussed above, are more prevalent in cold exposed workers and cold working environments can also contribute to respiratory problems and greater menstrual pain in female workers [46–49]. These potential exposures mean employees need to be appropriately trained and properly outfitted for the prevailing conditions. Slippery platforms are an added safety concern when temperatures are near or below freezing. In the summer months, concerns switch to risks associated with heat exhaustion during intense, periods of physical labour, as well as to potential exposure to harmful UV rays.

4.8. SCUBA diving safety

Occupational diving is another physical risk that is common in finfish and pelagic shellfish grow-out systems. On a year-round basis, finfish grow-out operations require divers to perform numerous tasks including inspection of cage mesh integrity, attach/detach/service cage anchor mooring lines, and remove dead fish accumulated at the bottom of the cage. In pelagic shellfish grow-out systems, divers are responsible for attaching/detaching/servicing the long line from the anchor mooring, as well as inspecting the farmed animals. During harvest or grading, the long line is attached to a winch so that it may be hauled up to the ocean surface. The main dive-related hazard involves the risk of decompression sickness, which is associated with the expansion of gas bubbles upon a rapid change in atmospheric pressure, such as can occur with improper dive ascents or multiple ascents/descents in a short time frame [50]. Many of the aquaculture diving tasks require short, repetitive dives with heightened risk of decompression sickness. Confirmed cases of decompression sickness have been reported in aquaculture operations in some regions [24,50–52]. Other safety concerns associated with diving include the risk of underwater complications such as equipment failures, net entanglement and ocean currents, as well as surface hazards. Shellfish grow-out locations in some provinces, such as Prince Edward Island, are commonly ice-covered during some parts of the year opening up the possibility of getting trapped under the ice and of extreme cold exposures for divers.

Fisheries and aquaculture occupational diving risks have prompted all the provincial governments of Atlantic Canada to regulate such activities to standards set out by the Canadian Standards Association (CSA) [53,54].

4.9. Excessive noise exposure

Excessive noise exposure is another potential but understudied physical hazard associated with the aquaculture industry. There is a long and well-documented history of occupationally-induced hearing loss in many industries [55]. In aquaculture, potential exposure to excessive noise could be associated with working with feed blowers, motored vehicles and alongside machinery in fish processing plants and feed mills. Auditory safety solutions such as hearing protection are likely necessary to avoid both short-term and long-term hearing problems and associated mental fatigue in some jobs.

4.10. Confined spaces

Confined spaces can be described as space with restricted access points and poor ventilation. Associated hazards include working in close contact with moving mechanical parts or electrical equipment, exposure to extreme temperatures, loud noise, potentially increased exposure to vibration and respiratory exposure risks [56]. In aquaculture, confined spaces are found in association with feed silos/barge systems, pipelines, vessel holds, cold storage facilities and tanks. There has been one documented case where entry into a large, confined hatchery tank for cleaning resulted in a fatality due to the inhalation of hydrogen sulphide gas that had concentrated in the stagnant sludge water at the tank bottom [57]. Methane, a flammable asphyxiant [58] found in accumulated stores of fecal matter in sludge water, is another potentially dangerous gas associated with confined spaces. Confined space protocols are quite relevant to many operations in the aquaculture industry and need to be adopted and consistently followed.

4.2. Chemical hazards

Chemical agents serve a variety of functions in aquaculture related to disinfection, anaesthetization, pest control, freezing, cleaning, disease control and preservation. Due to food safety and environmental concerns, regulation for the use of some of these chemicals is rather strict with well-detailed health and safety information available for most compounds [59–61]. Table 2 summarizes the hazards associated with selected chemicals approved for use in Canadian aquaculture. Information on chemicals associated with mollusc treatment is sparse. Generally, aquaculture production-related chemicals pose limited occupational risk when handled by trained workers following the guidelines of the workplace hazardous materials information system (WHMIS).

There have been a few studies directly related to occupational chemical hazards in aquaculture. In the hatcheries considered, formaldehyde exposure has been shown to be below dangerous levels [62,63]. There is evidence from an Ontario study indicating the potential for unsafe levels of radon gas exposure, a carcinogen [64], in groundwater-sourced freshwater hatcheries with poor ventilation [65]. Similarly, hydrogen sulphide gas, an acute toxic inhalant [57,66] and carbon monoxide exposures [67] from vehicle exhausts have been recorded in some poorly ventilated hatcheries. Ammonia leaks are a major and enduring chemical hazard in seafood operations where freezing units use ammonia as a refrigerant [68]. Moreover some seafood products, particularly

Table 2
Notable chemicals approved for use in the Atlantic Canadian aquaculture industry [52–54]

Chemical	Product/brand name	Hazard
Disinfectants, Parasiticides, Fungicides and Antifoulants		
Benzalkonium chloride	Benzalkonium Chloride	General irritant; ingestion danger; toxic compounds produced upon combustion [103]
Chloramine T	Chloramine T, Halamid	General irritant; produces chlorine gas upon combustion [104]
Cupric oxide	Aquashield®; Flexguard®; other copper-based paints	Mild skin, eye and lung irritant [105]
Emamectin benzoate	SLICE®	General irritant; ingestion may cause various CNS effects [106]
Formaldehyde	Parasite-S®; Paracide-F®; Formalin-F™; Formacide-B	General irritant; combustible; inhalation danger; CNS depression [107]
Hydrogen peroxide	Hyperox; Perox-aid®	General irritant; corrosive; toxic; oxidizer [108]
Iodine	Various	Toxic [109]
Ivermectin	Stromectol®	General irritant; potential male reproductive effects [110]
Methanol	Parasite-S®	Flammable; toxic [111]
Sodium hydroxide	Biosolve	General irritant; corrosive [112]
Sodium hypochlorite	Bleach	Corrosive, poisonous, oxidizer [113]
Sulphamic acid	Antec Biofoam	General irritant; corrosive [114]
Teflubenzuron	Calicide®	Potential gastrointestinal or liver toxicant [115]
Potassium Peroxomonosulphate and Sodium alkyl benzene sulphonate	Virkon®	General irritant [116]
Anesthetics		
2-Phenoxyethanol	2-Phenoxyethanol	General irritant; potential effects to hematopoietic system [117]
Tricaine methanesulfonate	Finquel®; Tricaine-S	General irritant; corrosive [118]
Antibiotics		
Azamethiphos	Salmosan® 50 wp	General irritant [119]
Erythromycin	Gallimycin® line	General irritant; toxic [120]
Florfenicol	Aquaflor® line	General irritant; Linked to digestive, reproductive and developmental complications [121]
Oxytetracycline hypochloride/dihydrate	Oxymarine™; Oxytetracycline HCl Soluble Powder-343; TETROXY Aquatic; Terramycin-343; Terramycin-200; Oxysol-220; Oxyvet® 200 LA	General irritant [122]
Sulphadimethoxine and Ormetoprim	Romet® 30; Romet® TC	General irritant; potential birth defects; potential effects to hematopoietic system [123]
Trimethroprim and Sulphadiazine	Tribrissen® 40%	General irritant; ingestion may cause vomiting, headache and nausea [124]

raw products destined for export to Japan, are dipped in sulphites. Sulphite use can result in exposures that have been associated with the development of occupational asthma [69].

The principal respiratory concerns for aquaculture workers are related to the potential inhalation of dusts, gases, fumes and vapours [70,71]. There is potential for exposure to airborne chemicals and metals, such as vehicle exhaust gases [72], styrene exposures are associated with fiberglass boat repair and the use of treatment or cleaning chemicals can also contribute to respiratory problems [70].

4.3. Biological hazards

As in the traditional fishing industry, biological hazards are potentially widespread in the aquaculture industry. Potential biological hazards in aquaculture include handling animals with sharp teeth and/or spines and exposure to sharp bones and sharp shell fragments leading to the potential for bites, cuts, puncture wounds, related infections, as well as the risk of allergic reaction and disease. Exposures to aerosolized proteins can cause occupational allergy and asthma and exposures to bacterial and parasitic diseases have been associated with aquatic organism contact [20,27].

Dermatological conditions may be the most prevalent occupational health problems related to biological hazard exposure for workers in aquaculture. Unprotected skin contact with various shellfish and finfish tissues or fluids can lead to eczema, urticaria, chapped skin, itching and other similar symptoms [73–77]. Moreover, these symptoms can be amplified in the cold, moist environments that are commonplace in the industry [20,78,79]. The primary contact allergens have been identified as polypeptide molecules, such as enzymes [74–77,80,81]. The vast majority of the literature on skin problems has focused on the processing phase, presumably due to an enhanced likelihood of exposure induced by increased handling and dismembering. There are currently no data quantifying the amount of fish or shellfish handling that occurs at hatchery and grow-out operations or how prevalent dermatological conditions are among workers in these phases of the aquaculture industry. However, protective measures should be implemented wherever contact is likely to occur.

Respiratory conditions are another potential result of biological exposures, particularly for workers employed in processing and in feed milling facilities with poorly designed production processes and/or inadequate ventilation systems. Exposure to airborne proteins, endotoxins and various micro-organisms are a well documented cause of occupational allergy and, in some cases asthma in seafood processing including in the processing of aquacultured salmon [20–22,69,72,82–88]. Primary and secondary processing activities such as cleaning, dismembering and cooking can result in wet aerosol production and, consequently, worker inhalation hazards [20–22]. As with dermatological conditions, aerosolized allergens are a greater concern in the moist, often cold, seafood processing environments [20,89].

Fish feed is composed of an assortment of ingredients consisting of plant and animal proteins, oils, grains, seeds, vitamins, minerals and other additives [90,91]. The inhalation of dry aerosols produced from animal feeds is known to negatively affect some feed mill employees by causing such ailments as occupational asthma, chronic bronchitis, organic dust toxic syndrome and extrinsic allergic alveolitis [70,71,92].

Fish and shellfish can be carriers of numerous human pathogens such as *Vibrio*, *Salmonella*, *Streptococcus* and toxic dinoflagellate species [27,93]. Durborow [27] provides a detailed review of potentially harmful microorganisms that may be encountered when handling or consuming seafood products. Related primary research has focused on the relevance of pathogenic hazards for food safety rather than issues related to occupational safety. Fortunately, the diversity of harmful organisms that occur in the cold water aquaculture of Atlantic Canada is low relative to that associated with aquaculture in warm water climates. However, occupational exposure to dangerous microorganisms can occur through aerosol inhalation, broken skin, and ingestion [24,27,93–95]. Exposure through cuts and abrasions is of particular concern during fish processing. The risk of needle puncture wounds in hatchery or grow-out operations associated with vaccine administration or blood sampling also needs to be addressed. Vaccination of juvenile fish is common practice prior to transfer to grow-out facilities. During vaccination, each individual receives an intraperitonal needle injection and mistaken needle punctures and injections have been known to result in inflammatory and allergic type reactions [27,96,97]. Accidental ingestion caused by oral contact with contaminated hands is unlikely if employees are following appropriate operating protocols that emphasize cleanliness.

4.4. Psychosocial hazards

Pressured work environments associated with high demand and low control situations, employment uncertainty and shift work have been associated with work-related stress and associated psychological, physiological symptoms and related costs to quality of life [98–101]. To our knowledge, there has yet to be an analysis of the psychosocial hazards associated with employment in the aquaculture industry. However, by its nature, aquaculture is likely to share stress factors with similar fisheries/sea-based and agricultural occupations; among others. For instance, as is common in other marine occupations, remote grow-out operations can require employees to spend extended periods away from their families and homes [101]. Similarly, the cyclical patterns of farming characterized by rearing organisms through portions of their life cycle and the risks of losing an entire cohort of product to unintended mortality or poor growth events are obvious sources of stress for both employees and employers [102]. Shift work is common in the industry as is high-paced work.

4.5. Social, organizational and individual risk factors in the aquaculture industry

Industrial dynamism, cost-cutting measures, labour turnover, labour shortages, inexperience, a predominance of aging workers, poor education, limited literacy skills, employment vulnerability, limited knowledge of the dominant workplace language, as in the case of labour forces dominated by migrant workers, and regional limitations on access to OHS expertise can contribute not only to psychosocial hazards but to OHS risk in general. The aquaculture industry in Atlantic Canada and elsewhere shares with the fishing and fish processing industry vulnerability to many of these other contributing risk factors. Firstly, there is a lack of OHS training among health professionals in Atlantic Canada. These professionals are often the first point of contact between an injured or ill worker and the health care/compensation system and their lack of training may lead them to misdiagnose work-related health problems. Secondly, access to appropriately trained specialist employees such as electricians, welders, builders and divers may be quite limited in this region particularly in rural and remote contexts. Thirdly, job site organizational structure and labour shortages may contribute to risk factors such as working alone on the water, in confined spaces and other hazardous contexts increasing the risk of drowning, electrocution, and falls from height. In addition, the factors outlined above can contribute to under-reporting and mis-reporting, they can enhance the challenges facing joint occupational health and safety committees (JOHSC), employers, compensation and regulatory agencies and researchers seeking to promote safety in the industry.

5. Conclusion

Aquaculture is rapidly expanding both globally and within Atlantic Canada. The industry is dynamic, complex and aquaculture operations are often located in rural and remote, harsh environments. The results of very limited aquaculture OHS research to date and a detailed description of the various phases of the industry suggest there are multiple, potentially serious occupational hazards associated with the industry. In addition, a number of secondary factors may be contributing to risk and constraining reporting and regulation. In Canada, as in many other countries, the internal responsibility system for occupational health and safety requires employers to inform their workers of potential occupational hazards and to minimize, as much as possible, the potential risk of injury and disease associated with those hazards. Workers have the right to know about OHS risks; the right to participate in OHS improvement through their membership in JOHSC and through other means; and the right to refuse dangerous work. Contemporary compensation agencies generally also have a prevention responsibility and, in some cases, they are responsible for inspection; in other cases these inspection responsibilities fall to government.

Systematic hazard identification, education, training and prevention are essential requirements for a safe industry, as is systematic research to document hazards, evaluate risks, identify appropriate prevention initiatives and evaluate the effectiveness of those initiatives. Studies focused on WMSDs in aquaculture-related processing operations are needed. The design and implementation of ergonomic guidelines in aquaculture-related processing plants would also be beneficial. Employers must ensure forklift operators are properly trained and that they are operating in a safe environment. Thus it is important to ensure there is adequate visibility by, where necessary, increasing the size of open spaces and installing angled mirrors to eliminate blind spots. Minimizing the use of diesel and propane forklifts within plants and other enclosed areas, good maintenance of forklifts, provision of ventilation systems designed to prevent the re-entrainment or entry of diesel fumes from trucks and forklifts and proper and safe handling of cleaning chemicals could help reduce chemical risks in the aquaculture industry. Effective health and safety procedures including minimizing animal handling, training in safe animal handling, appropriate work design, appropriate enclosure and ventilation of aerosolized proteins and where all else fails appropriate use of effective personal protective equipment can limit the occupational health risks associated with biological hazards. All the grinding, mixing, forming and bagging activities involved in the manufacturing of feed can potentially expose employees to organic aerosols in poorly ventilated environments. Efficient ventilation systems that enclose aerosolizing processes and associated dusts and, as a last resort, the use of appropriate personal protective breathing devices can help reduce the risk of respiratory health problems.

Potential psychosocial factors associated with the aquaculture industry warrant further attention.

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