Reviews in Aquaculture

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Exposed Aquaculture Operations: Strategies for Safety and Fish Welfare

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ABSTRACT

The expansion of aquaculture production into more exposed harsh and remote ocean environments presents both new opportunities and challenges. To manage the complexities of exposed operations, research into fish welfare, personnel safety, and facilitating technology is thus of key importance. This paper reviews recent research advances in the areas of safety, fish welfare, and technology, while the focus is on the Norwegian salmon farming industry, the results could benefit exposed fish farming internationally. Regarding fish welfare, the study summarizes the current knowledge status of salmon coping abilities and welfare indicators in strong currents and waves. On the safety front, there has been significant progress in operational safety management, accident analysis, and emergency preparedness, all of which are crucial for human personnel in these demanding settings. Human safety and fish welfare also rely on structures and equipment, and recent research results include advances in environmental load analysis, vessel design, simulations of fish farms. Notably, the development of contact-free, autonomous lifting operations, and hole detection methods represents a significant leap in maintaining aquaculture infrastructure. This multidisciplinary study underscores the need for integrated research approaches to address exposed aquaculture, emphasizing that while recent innovations have enhanced safety and robustness, ongoing research and new strategies are critical for safety and fish welfare in exposed aquaculture operations.

1 | Introduction

Some of the controversies and problems surrounding aquaculture could be reduced if fish farming were moved to harsher and more exposed areas, but such a move also challenges fish welfare and personnel safety [1]. The present study focuses on those issues in the shift to exposed aquaculture, which is a particularly notable ambition in the Norwegian farming of Atlantic salmon (*Salmo salar*).

From its small-scale beginnings in sheltered coastal waters during the 1960s, salmon farming has evolved into a substantial industry that is vital for meeting growing needs for food and employment; however, it faces environmental and spatial constraints [2, 3]. Production volume has grown through increased efficiency, understanding and development of fish genetics, physiology and nutrition, number of farms, and increased dimensions of the rearing units and other infrastructure.

Exposed aquaculture is viewed as a solution for salmon farming, although it requires knowledge and strategies for fish welfare and safety, including structural integrity to ensure safe operations and fish welfare. Major advances have occurred in the field of exposed aquaculture since previous reviews focusing on technology [1] in 2015 and fish welfare [4] in 2020. The research landscape has evolved considerably in this period, which is also indicated in a recent review of common salmon farming innovations [2]. The present study aims to summarize the current state of research in exposed aquaculture, delving into the multidisciplinary challenges and the latest developments in fish welfare, safety management, and technological innovations supporting safety and fish welfare. By integrating insights from biology, engineering, hydrodynamics, and safety sciences, the study provides a comprehensive overview of the progress and ongoing needs in this emerging field of exposed aquaculture. While we acknowledge the broader context of aquaculture, our focus here is less on the commonalities shared with traditional aquaculture practices (Afewerki et al. [2] offer a review of industry status). In particular, the present study addresses the unique difficulties posed by harsh weather conditions, remote locations, and dynamic aquatic environments.

The remaining sections of this paper provide an analysis of the aspects important to safety and fish welfare in exposed aquaculture. These include adaptations in fish farming techniques to ensure optimal fish welfare under challenging conditions, advancements in safety management for protecting personnel in these high-risk environments, and the development of robust technologies and infrastructure capable of withstanding the extreme forces of the open ocean setting. Overall, the paper seeks to contribute to the growing body of knowledge about exposed aquaculture, highlighting the need for continued research and innovation for fish welfare and safe operations.

2 | Foundations for Exposed Aquaculture

The need for knowledge related to exposed aquaculture operations is based on the pursuits for new salmon farming sites in particular, and for aquaculture opportunities in general. This section introduces key requirements for salmon farming sites, and specific challenges of exposed aquaculture.

2.1 | Basic Conditions for Salmon Farming

Open net pens continue to be the primary technology for salmon farming, which relies on the quality and conditions of the natural marine environment, as well as other requirements making sites for salmon farming a scarce commodity.

2.1.1 | Natural Conditions for Salmon

Open sea settings provide a habitat for salmon and require careful site selection to ensure sustainable and viable farming. Key elements of a suitable site include clean seawater with stable temperatures between 8°C and 14°C, balanced salinity, along with strong enough currents to ensure oxygen replenishment and waste removal [4]. Additionally, the water should ideally maintain sufficiently low concentrations of parasites, such as the salmon sea louse (*Lepeophtheirus salmonis*), pathogens, algae, and jellyfish, to avoid any need for preventive measures or treatments.

2.1.2 | Other Salmon Farming Site Requirements

Selecting a farming site also requires consideration of its distance from other activities like marine traffic and other industries. Much of the world's coastal areas are already reserved for various purposes, including coastal fairways, fishing, natural reserves, military use, energy production, and existing fish farming [5]. Furthermore, biosecurity is a priority in site selection in order to prevent the transmission of pathogens and parasites between wild and farmed populations [2, 6]. An optimal location for salmon farming should be in appropriate zones of marine spatial plans, accessible and offer proximity to necessary infrastructure like land bases and slaughterhouses. The site must provide safe working conditions in all kinds of weather [7].

2.1.3 | Limited Sites Available for Salmon Farming, Resulting in Exploration of Exposed Sites

Despite advances in farming equipment and infrastructure [2], the industry faces a scarcity of sites that fulfill the many requirements for optimal salmon farming. While certain environmental factors like temperature, salinity, and weather are a given, factors like site remoteness and operational approaches can be adapted. For example, scaling down other coastal activities could free areas for fish farming under suitable natural conditions, though this would require significant changes across several industries and sectors of society [5]. However, given the controversies surrounding aquaculture and competing coastal space uses [6, 8, 9], a less conflict-laden approach might involve developing operations and infrastructure to enable farming in more weather-exposed sites: exposed aquaculture. This approach presents its own set of challenges and necessitates research and development, which is discussed in the next paragraph.

2.2 | Exposed Aquaculture as a Solution—And a Challenge

Exposed farming sites include both fjords with strong water currents and open ocean areas with high waves [1, 10]. Exposed aquaculture thus is a label for *existing* and *future*, *coastal* and *offshore* aquaculture at exposed locations. As last section showed in the case of Norwegian salmon farming, the expansion of the salmon farming industry into more challenging high-energy environments is driven by the need for sites with adequate conditions, but it also represents wider opportunities if challenges are solved.

2.2.1 | Exposed Aquaculture as an Answer to Global Demands

Internationally, there is a growing demand to identify new areas suitable for aquaculture, which would open up opportunities and provide benefits for the production of a variety of organisms like fish, shellfish, and seaweed. This expansion would not only support growth in existing industries—as indicated for salmon farming in Section 2.1—but could also foster new production and support livelihoods in local communities with rough coastal environments [11]. The use of new areas could impact local ecosystems and intersect with activities like oil and gas exploration, maritime traffic, and commercial fishing, and it would require a careful balance between operational expansion and environmental stewardship.

2.2.2 | Challenges and Knowledge Gaps for Exposed Aquaculture Operations

The successful development of exposed sites in general and for fish farming in particular requires new knowledge. Stormy weather, stronger currents, and higher waves significantly affect both the farmed fish and the operational processes and may lead to difficulties in maintaining reliable production [12–15]. At least for salmon farming, exposed sites involve many of the same operations as more sheltered sites, like feeding, removing dead fish, counting salmon lice, cleaning, surveillance, and maintaining nets and equipment [1, 16]. Exposed operations will still demand careful consideration for the sake of both human safety and fish welfare. In addition, exposed conditions require more sophisticated logistics and potentially increased automation and remote control to ensure continuous operations, especially during periods when such sites are inaccessible to personnel.

Thus, there is a need for strategies for safety and fish welfare in exposed aquaculture operations, including robust technology for aquaculture structures and safer operations. To understand the knowledge already gathered, key research on fish welfare, personnel safety, and technology is presented below.

3 | Fish Welfare at Exposed Sites

A crucial question for exposed aquaculture of Atlantic salmon is whether the fish can thrive in more extreme environments. The main concerns are their coping abilities in stronger water currents and higher waves. More specifically, the fish should maintain behavioral control by avoiding exhaustion or collisions with farm structures or other fish and have sufficient metabolic scope to grow and deal with the physiological demands imposed by the environment, parasites, pathogens, and operational procedures.

3.1 | Swimming Capabilities and Challenges

The swimming capacity of both Atlantic salmon and cleaner fish species has been extensively studied in recent years (see review by Hvas et al. [4]). In addition to the magnitude and duration of current speed, several environmental and biological factors modulate swimming capabilities, with temperature, body size, and health status particularly important in that regard. Water currents, which may vary in intensity at different depths, and the impact of wave motion, which decreases with depth, are significant factors. Salmon can escape waves by diving, with a range of trade-offs coming into play, such as speed of currents, surface attraction for favorable light, temperature levels, feed, and high local stocking densities.

Atlantic salmon have different swimming modes. In low water currents like those found at conventional salmon farming sites, they swim at voluntary speeds (0.5–1.5 body lengths s^{-1}) [17, 18] and in circular schools [19, 20]. However, if the water current exceeds their preferred swimming speed, individual and group behavior changes to maintaining a stationary position against the current [19, 20]. Prolonged exposure to strong currents may inhibit feeding and growth and eventually cause fatigue [21–23].

Atlantic salmon are superlative marathon swimmers. Critical swimming speed (U_{crit}) is a standard method for investigating the maximum speed a fish can maintain over short (15–30 min) test intervals and is excellent for assessing the effects of biological and environmental factors on swimming capacity. Salmon can maintain strictly aerobic swimming (sustained swimming capacity) up to 80%–85% of its critical swimming speed and have been found able to endure 72 h of constant swimming at that magnitude [24, 25]. However, once this aerobic threshold is exceeded, the fish become exhausted within minutes to hours [24]. Water current speeds may be heavily impacted by cyclic wave forces, where Atlantic salmon tested for sustained swimming capacity under wave-like fluctuating water currents endured ~20% higher peak speeds than under constant current conditions [26].

Several conditions are known to influence fish swimming capacity. Atlantic salmon have a wide thermal interval in which they can maintain good swimming performance, where aerobic scope and U_{crit} is reduced toward the colder end of their thermal spectrum [27]. Parasites and diseases can negatively affect salmon swimming capacity by elevated metabolic demands and reduced oxygen uptake by, for example, amoebic gill disease [28–30]. Likewise, poor oxygen availability reduces swimming performance [17]. At exposed sites, supply chain issues or persistent stormy weather could cause periods where fish cannot be fed, but Atlantic salmon are robust to extended fasting as they can maintain critical and sustained swimming speeds over a 4-week fasting period [23, 31].

By contrast, cleaner fish like lumpfish (*Cyclopterus lumpus*) and ballan wrasse (*Labrus bergylta*) fundamentally differ from Atlantic salmon in their swimming capacities, stress responses, hypoxia tolerances, and thermal preferences, which altogether make them unfit for exposed farming [32–34]. In general, there is tremendous concern about cleaner fish welfare and the ethical implications of using another vertebrate for parasite control, something that is not done at industrial scale in any other type of food production.

3.2 | Coping With Waves and Current

Fish coping mechanisms regarding waves and water currents have been studied in exposed sea cages using cameras and echo sounders [35, 36]; the results show that wave parameters, currents, and time of day (i.e., light) influence fish behavior and their vertical distribution. During the day, hydrodynamic conditions exert a stronger influence on vertical distribution than at night. In weak currents, fish generally stay deeper in the water in response to taller waves, while stronger currents generally cause them to move upwards regardless of wave conditions.

Still, large waves appear to induce the fish to shift from the exposed side of the cage to the more sheltered side. This highlights important coping mechanisms in salmon toward exposed conditions and suggests that they should be provided with deep enough cages to enable escape from wave forces and potential net deformations. In addition, recent measurements in Norway [37] using deeper cages and similar wave heights found that salmon did not swim far away from waves despite being provided a deeper option, suggesting that salmon may only avoid waves to a certain extent under medium wave exposure (Hs 1–2 m) [37]. Salmon also show strong horizontal preferences, generally occupying the portions of the cage exposed to currents during calm weather. The effect of wave-induced turbulence as tested in lab showed that salmon over weeks fully adapted to a more chaotic environment, which highlight the flexibility of the species toward wave exposure [38]. The current understanding of salmon coping ability under exposed farming conditions, drawn from lab and case studies, provides insights and guidelines for current and future farming practices [4]. However, there is still much to explore regarding how salmon handle challenges like ocean swells, welfare risks connected with interactions of large predators, and the impact of rearing technology and fish group sizes, where, for example, upscaling of biomass may increase the risk of hypoxia during low current periods [39, 40]. Further investigation upon deployment of open ocean farming is needed to address these aspects.

3.3 | Solutions for Measuring Fish Welfare

Verified observation tools for online assessment and documentation of fish welfare and environmental conditions are fundamental to the knowledge-based development of exposed fish farming [41]. While visual observation from surface or submerged cameras of the swimming behavior of fish groups and individuals remains valuable for assessing how they deal with their environment, more detailed and continuous logging is required. Technological solutions building on knowledge of the relationships between fish energetics and behavior, their environment and spatial distributions can record vital parameters to identify the impacts of both the rearing environment and operational procedures.

Simulation models can be used to understand how fish behave at the farm during different types of weather. One study monitored the difference in behavior among fish from the same group but reared in different cages in the same farm that had differences in exposure [42]. An avoidance criterion was implemented to simulate fish behavior in waves, based on an integrated numerical model of fish and a flexible sea cage. The simulation model was found to be able to reproduce the observed fish distributions in general, while more data are needed for parameterization and verification of their extended behavioral expressions [42].

A welfare-based classification method of ocean current speeds can be used to evaluate suitability from a fish welfare perspective [43]. Considering our present knowledge of Atlantic salmon swimming capacities and current speeds in Norwegian waters, it can be concluded that vast ocean areas are suitable for salmon farming [24].

The relationships between salmon tail-beat frequency, swimming speed, metabolic rate, and heart rate, as measured in detailed laboratory studies, have been examined to generate standard curves that can be used in further research [24]. Recent developments in individual fish tags allow for the continuous data sampling of both movement speed [44, 45] and tail-beat frequency and amplitude [46]. The heart rate of salmon can also be measured with tags, but corresponds less with oxygen consumption rates at low and high swimming speeds than the other parameters. However, heart rate may be an excellent indicator of stress level and recovery [23, 47–50]. It is thus feasible to collect detailed individual data that can be used to estimate energy use and understand the coping abilities of fish under exposed conditions.

Echo sounders can record the spatial distribution and density of fish in the vast volumes of sea cages and are well suited to the assessment of group-level behavior. For example, a comparison of fish distribution between two strategically positioned transducers can document when strong water currents force fish to aggregate on one side of the cage and the extent to which fish move away from waves [35, 51]. Måløy [52] created a deep-learning model called EchoBERT to process echo sound data and classify and automatically detect group behavior in caged salmon. That model shows significant potential in extracting useful information and thereby provides early warnings of deteriorating health or environmental conditions. Such may also be done at individual fish level by automatic identification in images [51].

4 | Personnel Safety in Exposed Aquaculture Operations

This section addresses key risk dimensions, safety management, operational decision-making, and measures to mitigate health and safety risks for personnel working at exposed sites.

4.1 | Occupational Hazards for Personnel

Personnel in the aquaculture industry globally are at increased risk when it comes to occupational diseases and injuries [53]. Both hazards and regulations in aquaculture are diverse, and a global commitment to occupational health and safety issues for aquaculture personnel is urgently needed [54].

In salmon farming, especially at exposed sites, environmental factors significantly impact worker safety during operations [55]. Outdoor working conditions, which are of course subject to wind, waves, and currents, present key challenges. Injury rates at these sites are higher during the fall and winter [56], suggesting increased risks in environments with stronger winds and higher waves.

In Norway, the rate of occupational injuries and fatalities in fish farming is notably higher than in most other industries except for commercial fishing [57]. Data from the Norwegian Labour Inspection Agency show that from 2011 to 2019, the injury rate ranged between 50 and 60 per 10,000 person-years, with an upward trend from 55 in 2017 to 73 in 2019. On average, there has been one fatal accident per year in the Norwegian industry from 2012 to 2020 [55]. Common injury types include falls, blows by objects, entanglement or crushes, and lacerations. Crane and capstan operations are particularly hazardous, with most fatal accidents since the turn of the millennium linked to incidents during lifting and maintenance operations [56, 58].

Manual labor is a central part of daily work at fish farms, and ergonomic risks such as lifting with the upper body twisted or bent, repetitive and monotonous tasks, and heavy lifting in general are common causes of musculoskeletal pain. Workers report that tasks like inspections, dead fish removal, changing heavy batteries, hauling nets, cleaning nets, and counting lice are particularly straining [59, 60]. High workloads are common [61], and over half the workers expressed concerns on an occupational health and safety survey about negative health impacts from their work environment. The most common complaints were pain in the neck, shoulders, and arms, in the back, and in hands and wrists, with strain injuries a major cause of work-related sick leave [60].

4.2 | Safety Management

Accidents in aquaculture are sometimes attributed to human error, with the common view that humans, while being central to fish farm operations, also represent a vulnerability within the system:

> Humans are the hub in the fish farm operation system but are also perceived as the weak link of same [55, p. 68].

However, studies find that underlying causes are often organizational. Examples of organizational risk influencing factors are insufficient staffing, a lack of adequate training, poor planning, and insufficient time allocated for maintenance [62–64]. Moreover, the safety climate within an organization can affect workers' health, with links observed between work pressure, lack of involvement in safety decisions, and health complaints like headaches, fatigue, and musculoskeletal pain [65].

While there is a consensus among managers and operating personnel that systematic safety work has improved, there is also a belief that safety management systems could be more effectively integrated into daily activities. The regulatory focus on safety management has increased in recent years [63], leading to a shift from specific safety rules to more function-based regulatory requirements and resulting in an increase in internal company procedures [66]. Research has shown that internal procedures are perceived as overly complex [65, 66], and there is a noted lack of personnel involvement in the risk assessment analysis phase [67].

4.3 | Balancing Operational Decisions

In aquaculture, there is often a tension between the objectives of protection and production [68], and some employees feel that production is prioritized at the expense of safety [60, 69]. This may be related to organizational factors such as long work shifts and heavy workloads during large operations, which may in turn be connected to regulatory requirements.

Salmon lice infestations and fish escape remain major driving forces for regulation and technology development [70]. In Norway, due to regulations to combat salmon lice, delousing operations have become highly important to ensure that lice numbers on individual fish are below permissible limits [6, 68]. However, personnel involved in these operations often report extremely long working hours, sometimes extending up to 20 h a day, for several days in a row [60]. Delousing is not only stressful for workers but is also linked to decreased fish welfare and increased risks of escape and fish mortality [62, 68, 71, 72]. Moreover, studies have found that personnel safety may be compromised to prevent the escape of fish [62, 69]. Given these complexities, a holistic approach to risk management is necessary.

4.4 | Enhancing Risk Assessment and Safety Management

Safety management includes systematic activities that aim to prevent accidents and injuries and manage safety hazards in an organization. These activities include tools such as risk assessments, accident investigations, nonconformity reporting, safety indicators, and safety audits [55].

Holmen, Utne, and Haugen [67] suggest a workshop-based approach to risk assessment. This method focuses on directly involving fish farm and service vessel personnel in identifying hazards and undesirable events and discussing how they might be mitigated. This participatory approach allows for a comprehensive view of risks, considering factors such as personnel, environmental impacts like fish escape, fish health and welfare, infrastructure, vessels, and food safety [73]. Discussions with fish farm personnel show that fish welfare is highly important during operations such as delousing [12, 68]. Technology suppliers should include this knowledge in their design processes to ensure user involvement and reduce risks [74]. Historically, personnel safety has not been a focus of technology development within the industry. Ideally, the operation of a farm should be planned in the concept development phase to assess operational risks [55, 65].

Overregulation is a common concern of aquaculture companies [66], suggesting a need to better integrate safety management systems into daily routines [63, 75]. Safety measures that align well with the everyday reality of workers are generally more effective and relevant [76]. Fish farmers are required to report incidents to authorities, including those related to fish health, escapes, environmental emissions, food safety, and occupational safety. These reports are used to aggregate data for monitoring safety performance and identifying any necessary measures [55]. Regarding escapes, organizational factors like planning, training, staffing, and working hours, along with operational and maintenance practices, must be examined [71]. Based on analysis of previous escapes, escape scenarios can be developed to show hazardous events, direct and underlying factors, and risk-influencing or coupling factors [77].

Lastly, safety indicators may be a useful tool for monitoring safety, supporting decision-making, and detecting the need for risk-reducing measures—whether organizational or technical. This can be accomplished through a six-step method for identifying operational safety indicators in aquaculture [78]. The purpose of this method is to provide a tool to systematically define causal chains consisting of indirect and direct contributing causes and factors that may evolve into an undesired event or accident. The resulting graphical network of causal chains is the basis for identifying risk-influencing factors (RIFs). Safety indicators are parameters that measure the change in the condition of each RIF. Each RIF may be monitored by one or several safety indicators, which can be expressed by numbers or qualitatively. The steps of the method are as follows:

1. Identify the causes of the type of accident to be examined.
2. Describe the relevant work operations of high risk.
3. Develop a Bayesian network for the accident to illustrate causal chains.
4. Identify RIFs for each condition/event contributing to the accident.
5. Develop safety indicators for measuring the condition of each RIF.
6. Evaluate the safety indicators according to quality criteria.

The method was developed in cooperation with fish farming companies in Norway and evaluated using fish escape accident reporting data [78].

4.5 | Enhancing Operational Planning and Emergency Preparedness

In aquaculture, unlike many other marine industries, the use of operational limits is not commonly part of the planning and execution of operations [79]. Typically, decisions on whether to commence or abort an aquaculture operation are based largely on subjective judgments [80]. An additional challenge is that operational decisions also need to take fish welfare and the risk of fish escape into account. This means that when fish handling is involved, the operational limits cannot be based solely on environmental design criteria; the health status of the fish prior to and during operations also needs to be considered.

In more severe weather conditions, the interaction forces between vessels and structures increase, necessitating careful management of local contact forces, the forces in the mooring system, and their relative motions. Numerical models can establish environmental design limitations for vessel operations close to cage systems, for both moored vessels and those using dynamic positioning (DP). One example is a model using software like SIMO and RIFLEX in SIMA [81], which can simulate system responses like mooring line tension and vessel motion in a typical marine environment. The results of these simulations can support operational planning and decision-making, highlighting the growing importance of decision support systems that use objective operational limits to ensure safe aquaculture operations.

Operational efficiency can also be optimized through models that find optimal routes and schedules for vessels, maximizing profit while considering various constraints [82]. Such a model has proven effective in finding near-optimal solutions for managing fleets of vessels serving numerous fish farms under different weather conditions [83].

As aquaculture moves further offshore, emergency preparedness become increasingly critical [13]. Factors like larger farms, changes in work organization, automation, and more complex logistics will alter future accident scenarios [84], and a systematic approach to emergency preparedness tailored to the aquaculture industry is essential [85]. Research by Slette et al. [86] focuses on emergency responses by well boats in large-scale fish welfare emergencies, offering methods to estimate emergency outcomes and improve logistics in emergency response planning. That research was motivated by the mass mortality of fish following a harmful algal bloom in Norway in 2019, underscoring the need for better strategic and operational planning in emergencies [87].

5 | Technology for Exposed Aquaculture

Exposed aquaculture operations that are safe for both fish and personnel must be facilitated by the surrounding technology. This section is about structures, vessels, cranes, and remotely operated vehicles (ROVs).

5.1 | Structures

Exposed aquaculture allows for the exploration of new open ocean and remote sites, potentially involving larger facilities, innovative designs, and novel concepts [2, 3]. This includes upscaling of current structures, adopting designs inspired by the oil and gas sector, and incorporating mobile vessels [1, 88].

While flexible circular cages currently dominate the market, incremental improvements in conventional plastic rings are being paralleled by potentially groundbreaking innovations for exposed fish farming [1, 2, 88, 89]. In Norway, a government license regime has catalyzed several new concepts for open ocean fish farming [88] that have international counterparts like China's semi-submersible rigid Shenlan, Italy's submersible REFA Tension leg cage, and the Aquapod in the United States. Research in this field involves physical measurements and modeling of waves and currents, statistical analysis, numerical strength analysis, and model testing in hydrodynamic laboratories.

In structural design of fish farms, understanding wave characteristics and current velocities at potential aquaculture sites is essential. An effective design relies on comprehensive measurements, long-term statistics, and precise modeling [90–93]. Studies have identified shortcomings in established methods to determine design values for environmental loads acting on aquaculture structures [92], thus, Eidnes et al. [94] suggested extending measurements of water current velocities at aquaculture sites from one to 12 months, with a minimum of 3 months. New safety factors for structural design have also been offered, and these results were included in revised Norwegian technical standards issued in 2020 [95].

Drag loads on aquaculture nets are a major contribution to hydrodynamic loads acting on fish farms. Improved models for estimating these loads consider a range of factors like flow velocity, net geometry (size of structure, netting solidity, shape, and deformations), and the net's water resistance (drag coefficients). Numerical analyses have been applied to model these hydrodynamic loads and the structural responses of fish farms [96–99]. An accurate representation of a net's deformed

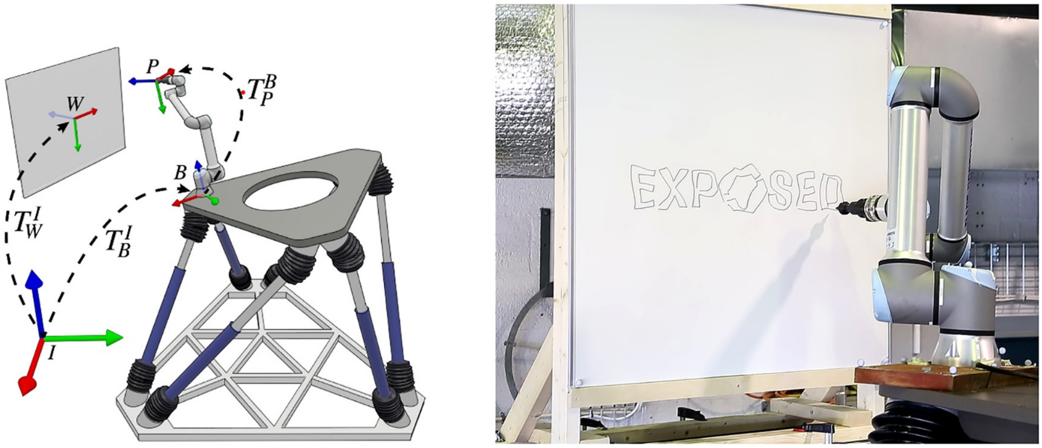

FIGURE 1 | Experimental setup with robot arm mounted on hexapod (left), snapshot of robot arm motion compensation performance test (right). Figures originally published in Brandt et al. [114].

shape in strength analysis is vital [100]. Drag loads are proportional to drag coefficient, a parameter that reflects the water resistance of the net, which in turn depends on net solidity, orientation, and possibly local geometry. The drag coefficient has been established for typical netting materials applied in net cages for fish farming based on towing tests of netting panels [101, 102]. Føre, Endresen, and Bjelland [101] established a new semiempirical load model for drag loads on aquaculture nets based on updated coefficients and solidity measures.

5.2 | Vessels

The shift of aquaculture farms to more exposed locations, significantly impacts vessel operations. This change introduces complex challenges, especially under severe wind, wave, and current conditions that affect the interactions between vessels, structures, personnel, and fish. In Norway, over 1300 vessels support approximately a 1000 registered fish farming sites [103, 104]. Between 2014 and 2019, more than 50 service vessels, well boats, and slaughter vessels have been delivered annually to Norwegian shipowners [105].

In exposed environments, rough weather conditions complicate operations involving vessels and fish cages. In manual operations, there are elevated risks associated with slips, trips, and falls on the vessel deck, the net cage, and during transfer between the two [80]. For a more detailed discussion of safety challenges and solutions in operations and logistics, see Section 3.

Designing vessels for operations in exposed areas requires specific considerations to ensure safety and efficiency [79]. The tasks and use of these vessels are diverse, and will be expanded for new types of operations. Some vessels will need seaworthiness superior to those of the current fleet, which serves more sheltered coastal areas. Improvements can be achieved through various means, such as operational planning, using larger vessels, optimizing vessel arrangement and hull design, and implementing active or passive motion compensation systems, including roll dampening technologies. A comprehensive design methodology for service vessels integrating vessel design, deck equipment, vessel capabilities, and operational safety for exposed aquaculture has been developed [106, 107].

5.3 | Cranes

Cranes are integral to aquaculture operations where vessels are involved, and crane operations are considered the most hazardous [108]. Cranes are commonly used for a range of lifting operations, from launch and recovery of ROVs to and from fish cages, removal of dead fish, and delivery of feed. Crowding operations that involve synchronous lifts by multiple cranes across several vessels are particularly complex and often require horizontal pulling. Notably, the improper use of crane equipment has been cited as a factor in numerous accidents.

The offshore petroleum industry has long used advanced crane technologies like heave-compensation, anti-pendulum, and automated ROV launch and recovery systems. Research in this industry includes Tysse et al. [109], who developed a controller for stabilizing crane load pendulum dynamics and validated it on a small-scale knuckle boom crane, and Tordal and Hovland [110], who investigated motion compensation for vessel-to-vessel load handling with cranes. There is also a range of semiautomatic connect and release equipment on the market [111]. However, its adoption in aquaculture has been minimal.

In exposed aquaculture operations, the limited window for safe operations presents significant challenges [12], necessitating a rethinking of standard procedures and potentially a shift toward increased automation and contact-free operations that operations would involve station-keeping near cages without mooring using technologies like manipulator arms rather than traditional cranes [16].

Research exploring the use of robotic arms in these settings has shown promising results [112]. Studies have simulated the station-keeping of a vessel at exposed aquaculture sites, demonstrating that a robot arm can effectively compensate for the motion induced and follow predefined trajectories under slow vessel movements (see Figure 1). However, issues with tracking errors in rougher sea conditions have been observed, leading to further research into reinforced learning to mitigate actuation delays [113]. Experiments have evaluated the feasibility of using vessel-mounted robotic arms for tasks like the automated removal of dead fish [112].

Despite these advances, several areas require further investigation, including the impact of a full-scale arm's configuration, link length, weight, speed, and structural stiffness on performance, the necessary sensor systems for object detection and tracking, and the overall operational capability of robotic manipulator arms in performing relevant aquaculture tasks.

5.4 | Remotely Operated Vehicles

Inspecting net pens is an important task in fish farming to ensure the integrity of the structure and prevent escapees. Inspections are carried out by divers or by using ROVs. At exposed locations, the possibility of using divers is limited due to harsher conditions, highlighting the need for more autonomous ROV operations. Those require localization, guidance, and control, which is particularly challenging with flexible cage structures.

Innovations in autonomous ROV operations have been explored in many studies. Grøtli et al. [115] analyzed autonomous behaviors in ROV inspection, while Karlsen et al. [116] tested a mission control architecture for ROV net inspection during full-scale trials. Various methods for ROV localization and navigation, such as hydroacoustic sensors [117] and laser camera triangulation [118] have been studied. The 3D laser triangulation data were compared experimentally with a Doppler velocity log (DVL) in an active fish farm; the results show that the laser camera system is comparable in performance to a DVL in terms of distance and angular pose measurements. Laser triangulation is promising as a short-distance ranging and net pose sensor for autonomous vehicles and is less expensive than acoustic sensors. Bjerkeng et al. [119] fused laser camera triangulation pose measurements with a compass heading, primarily to achieve global ROV localization within a cylindrical net pen. In Sandøy et al. [120], a forward-looking sonar was fused with odometry data to simultaneously map the environment and localize the underwater vehicle on that map. A method for estimating the position of acoustic transmitter tags on an anchor line has been developed [121] to provide a probabilistic representation of the environment for underwater vehicles operating close to or within the structure. Further results on probabilistic frameworks for simultaneous localization and mapping within aquaculture can be found in Sandøy [122]. Schellewald, Stahl, and Kelasidi [123] investigated a pure computer vision system for estimating the distance from a camera to a regular net structure in an aquaculture installation.

Earlier research has relied on simplifications, like assuming that net pens are perfect cylinders or cones, so further investigation is needed of complex scenarios like large cage deformations, severely folded nets, and obscured sensor views due to fish or lighting conditions. The above review shows that robust navigation solutions thus remain a key area for development.

Arnesen, Lekkas, and Schjølberg [124, 125] looked into path following and tracking for inspection ROVs, developing a control scheme for autonomously following net pen wall segments. This allows the operator to specify the desired ROV speed and distance relative to the net pen. The solution, validated both in the laboratory and during sea trials, adapts to environmental influences and ROV modeling uncertainties [126]. Although Arnesen et al. achieved validation of the method in a full-scale operational fish farm, safety regulations limit field trials in rough weather conditions, suggesting the need for further testing, perhaps in laboratories where open sea's harsh environmental conditions can be simulated.

Autonomous maintenance and repair with ROVs pose even greater challenges, as they require the ROV to be in contact with the cage. Drawing from subsea petroleum interventions, underwater grasping research has seen significant development (for example [127, 128]). Grasping an underwater object in a basin based on monocular vision, for instance, has been demonstrated [129], and more results on the use of robotic arms for aquaculture operations can be found in Haugaløkken [130]. Many of the challenges related to detection, grasping, and manipulation of objects are similar to those found using manipulator arms in contact-free operations from vessels; see Section 5.3. Some important distinctions are that since commercial ROVs often have arms with only a few degrees of freedom, joint control of vehicle and arm might be necessary due to the strong coupling effects and that underwater detection and tracking of objects are more challenging in general. Net repair and patching tools have been demonstrated, with solutions starting to become commercially available, although only limited published research is available. Net crawlers are a different type of vehicle that constantly move along the net, serving both for inspection and for the prevention of biofouling [131].

Permanent or semipermanent solutions where the ROVs reside at the fish farm have been proposed as an alternative to launch and recovery for every operation [132]. These residential solutions are likely to require a docking station to protect themselves in bad weather, to charge and transfer large amounts of data. In our opinion, resident ROVs face challenges in ruggedness, maintenance, and farm accessibility. Accessing multiple cages could be solved using multiple ROVs, with the drawback of additional costs. We have also proposed underwater swimming tunnels as an alternative to allow ROVs access to and from cages, although that approach would add to the complexity of cage structures.

6 | Conclusion

The expansion of aquaculture into more exposed environments is often associated with new technology, but also requires strategies for fish welfare and human safety. Fish welfare, safety, and technology must be viewed as a whole. In one sense, safety in aquaculture operations is not limited to human operators but also extends to the welfare of the fish. Stressful conditions for fish caused by environmental conditions or operations may lead to health issues that affect fish welfare and farm productivity. Vice versa, ensuring the well-being of fish directly correlates with the operational safety and efficiency of aquaculture farms: for example, the development of solutions for improved monitoring of fish health can mitigate risks, leading to safer and more sustainable conditions for fish and personnel. The present study has encapsulated existing knowledge about fish welfare, human safety, and technology that can be employed to develop further strategies for exposed aquaculture operations.

Our understanding of fish welfare at exposed sites has improved, particularly in assessing the swimming capabilities and behavior of salmon under challenging environmental conditions. Technological advances have facilitated more precise and continuous monitoring of fish welfare, enabling better management and adaptation to the dynamic conditions of exposed sites.

Safety management for personnel in these exposed operations has also evolved, with significant strides made in safety management, safety indicator methods [78], accident prevention, risk assessment, emergency preparedness, operational limits, and logistical optimization. This review has shown not only the challenges in controlling hazards of weather, training, competence, and organization of work and regulation but also improvements in strategies for risk assessment. Advancements in technology play a pivotal role in harmonizing fish welfare with operational safety. The development of robust structural designs for net pens in exposed environments reduces the risk of fish escapes and predator intrusions, safeguarding fish welfare while minimizing risk to human operators during maintenance and inspection activities. Additionally, the use of ROVs and autonomous monitoring systems both enhances the safety of human operators by reducing direct exposure to hazardous conditions and allows for continuous monitoring of fish health and environmental parameters, thus ensuring optimal living conditions for the fish.

The interplay between safety, fish welfare, and technology in exposed aquaculture operations is dynamic and complex that requires a multidisciplinary approach to address in appropriate depth. By understanding and leveraging the synergies between these aspects, aquaculture operations can achieve higher standards of safety, welfare, and efficiency. As the industry continues to evolve and face new challenges, the integration of these components will be crucial for sustainable and responsible growth.

Despite these advances, the presents study has made clear that meaningful challenges remain. The exposure of aquaculture operations to severe weather conditions necessitates ongoing research and innovation. Continuous efforts are needed to improve operational efficiency, ensure the welfare of both fish and personnel, and maintain the sustainability and resilience of the industry in the face of changing environmental and climatic conditions.

In conclusion, the path ahead for exposed aquaculture operations requires a multidisciplinary approach and collaborative efforts among researchers, industry stakeholders, and regulators to ensure safe and sustainable aquaculture in these new frontiers.

Author Contributions

Hans Vanhauwaert Bjelland: conceptualization, investigation, writing – original draft, writing – review and editing, methodology, project administration, resources, supervision, funding acquisition. **Ole Folkedal:** data curation, supervision, writing – original draft, writing – review and editing, methodology, project administration, investigation. **Heidi Moe Føre:** writing – original draft, funding acquisition, investigation, methodology, writing – review and editing, project administration, formal analysis. **Esten Ingar Grøtli:** data curation, software, formal analysis, project administration, methodology, writing – review and editing, writing – original draft, funding acquisition, investigation, visualization. **Ingunn Marie Holmen:** investigation, funding acquisition, writing – original draft, methodology, software, project administration, writing – review and editing. **Eivind Lona:** investigation, writing – original draft, validation, formal analysis, project administration. **Hans Tobias Slette:** investigation, writing – original draft, writing – review and editing, methodology. **Kristine Vedal Størkersen:** conceptualization, writing – original draft, writing – review and editing, project administration, formal analysis. **Trine Thorvaldsen:** investigation, methodology, writing – original draft, writing – review and editing, project administration.

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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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