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Short communication

Survey findings of disinfection strategies at selected Norwegian and North American land-based RAS facilities: A comparative insight

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ABSTRACT

Disinfection is an integral component of establishing effective biosecurity, through preventing pathogen introduction and transmission within and between aquaculture facilities. Nonetheless, there is a lack of documentation on aquaculture facility disinfection practices and strategies, thereby posing a challenge to benchmarking the current status and to determining optimal approaches. To gain a contemporary insight in this area, an internet-hosted survey was conducted for selected Atlantic salmon recirculation aquaculture (RAS) facilities in Norway (NO) and North America (NA, i.e., USA and Canada). The survey focused on the disinfection of materials and equipment in a RAS facility, and did not cover water disinfection. A total of nine facilities in NO and 16 in NA participated in the survey, which was conducted between Q2 and Q4 of 2018. Most of the responding facilities had standardised disinfection protocols (NO: 6/9; NA: 15/16); however, many respondents disclosed that their protocols had not been experimentally validated. The age of disinfection protocols was between 4 and 10 years old, with the majority of respondents regularly performing protocol appraisals. More than 80% of the facilities in both regions reported a compliance rate of 90–100%. Survey results indicated that peracetic acid-based disinfectants are the most commonly used chemicals in NO, while chlorine is predominant in NA. These disinfectants are used for the tanks and pipelines, floor, and ancillary equipment. In NO, the three topmost criteria when selecting a disinfectant were efficacy against pathogens, user safety, and ease of application. While efficacy and user safety are also prioritised in NA, it was also reported that threats of toxic residuals are also highly considered. Only one facility in NO and five in NA experienced a disease outbreak in the last 5 years. The survey responses presented the current state of aquaculture disinfection of representative land-based RAS facilities in both regions, and this information will be valuable in future benchmarking to develop robust and comprehensive disinfection strategies in salmon aquaculture.

1. Introduction

The global world population is increasing at a dramatic rate, and this consequently entails greater food needs. From the food-producing sector, aquaculture remains the fastest-growing industry, and the increasing production of farmed seafood in the last decade underlines the role of aquaculture in meeting growing consumer demand. Aquaculture production is projected to reach 109 million tonnes in 2030, an increase of about 32% from 2018 (FAO, 2020). The drive to further develop aquaculture as a major commodity-provider is anchored in several United Nations Sustainability Development Goals, including 1. *No poverty*, 2. *Zero hunger*, 12. *Responsible consumption and production*, 13. *Climate action*, and 14. *Life on water*.

Successful and sustainable aquaculture requires effective and efficient control of the rearing environment to provide fish with the optimal conditions for growth, as well as a thriving environment that fosters superior welfare (Cabillon and Lazado, 2019). There are, however, considerable challenges that present limitations to production and sustainability of the sector. Disease outbreaks, from persistent or emerging pathogens, remain a significant bottleneck causing substantial economic losses to aquaculture producers (Romano and Sinha, 2020). Hence, strategies must be in place to prevent and control pathogen entry and transmission in rearing systems (Bentzon-Tilia et al., 2016). Disinfection is a constituent element of the aquaculture facility's biosecurity measures, and it plays a crucial role in ensuring that on-site practices do not allow the entry, growth, spread, and exit of pathogens (Summerfelt et al., 2009). The general governing principles of aquaculture disinfection highlight the application of chemical treatments in

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adequate concentrations, and for sufficient contact time, to kill/inactivate all pathogenic organisms that would otherwise gain access to the surrounding water, and persist and proliferate in the system (OIE, 2003).

Despite having a consensus among producers on the importance of disinfection and several published recommended guidelines (Fiskeridepartementet, 2008; OIE, 2003; Yanong and Erlacher-Reid, 2012), there is a lack of documentation on the current status of disinfection strategies in aquaculture. This is particularly relevant in Atlantic salmon aquaculture, in which production technologies have advanced significantly in recent years (Terjesen et al., 2013; Ytrestøyl et al., 2020). Many facilities, particularly in Norway, are intensifying production by adapting recirculating aquaculture system (RAS) technologies during the land-phase of the production cycle, which is a significant shift from traditional flow-through or partial water reuse systems. These changes require a reassessment of current disinfection practices, as it will allow benchmarking and streamlining of protocols that are adaptive to the present demands of the systems and production practices. Re-evaluating disinfection practices would also allow the identification of critical points for revision and recalibration.

To gain a better insight into the present status of disinfection strategies in aquaculture establishments, a survey was conducted targeting selected Atlantic salmon producers in Norway and North America. The two regions were selected to provide a comparative understanding of the current landscape, thus facilitating the identification of similarities and differences between the two regions. The survey is part of the initiatives in CtrlAQUA SFI – a Centre for Research-Based Innovation in Closed-Containment Aquaculture (https://ctrlaqua.no/). It is anticipated that survey results will inform the centre in identifying research avenues that are responsive to present knowledge gaps.

2. Materials and methods

2.1. Questionnaire development

A questionnaire was developed covering key aspects of disinfection of materials and equipment in a RAS facility. It was divided into seven sections, including, 1) General information about the disinfection protocols, 2) Information on the disinfectants in use, 3) Disinfection protocols of tanks and pipelines, 4) Disinfection of ancillary equipment; 5) Floor disinfection; 6) Disease outbreaks and 7) Health and safety of staff. The questionnaire was hosted through an online survey development cloud-based software and conducted between Q2 and Q4 of 2018. The questionnaire was in Norwegian for the facilities in Norway and was later translated to English for the respondents in North America. The facilities were selected based on their known use of land-based RAS technologies. The survey did not specify the type of RAS technology being used in each site, was limited only to disinfection of materials and equipment, and did not include water disinfection.

2.2. Survey approach

A representative from each facility had been identified prior to the distribution of the questionnaire. In North America, some respondents were asked to disseminate the questionnaire to multiple locations within the same company. The forms were checked, and it was verified that responses came from a single facility; responses that did not cover more than 75% of the questions were not included in the collation of results. In general, the production manager at each location was the survey respondent. Table 1 details the locations and numbers of facilities surveyed. For confidentiality purposes, in this report the results are enumerated and discussed without mentioning company names and specific locations.

Table 1
Number of surveyed land-based RAS facilities and their locations.

Norway		North America	
Location	Number of RAS facilities	Location	Number of RAS facilities
Møre og Romsdal	2	Western Canada	2
Vestland	4	Atlantic Canada	7
Rogaland	3	Mid Atlantic, USA	3
		Pacific Northwest, USA	1
		Alaska, USA	1
		New England, USA	1
		Midwestern USA	1
Total	**9**	***Total***	**16**

3. Results and discussion

To our knowledge, this is the first initiative of its kind to profile the status of disinfection strategies in RAS facilities, thereby offering contemporary perspectives on the practices and approaches that are vital in streamlining the disinfection protocols that are adaptive to the current trends of both regions. The survey carried out in the two regions revealed interesting similarities and likewise identified remarkable differences.

Eleven questionnaires were returned from Norwegian respondents; however, two of these were invalid because more than 90% of the questions were not answered. The Norwegian summary discussed here is therefore based on responses from nine facilities total. All survey responses from North America were valid and were used in the reporting.

The first part of the questionnaire focused on the overall disinfection strategies of the facility, mainly on standardisation, compliance, appraisal, and reporting. Six out of the nine (66.7%) surveyed facilities in Norway responded that they had standardised disinfection protocols in-place; a standardised disinfection protocol is defined as a set of disinfection guidelines, either general or targeted, that are routinely followed in the facility. On the other hand, 15 out of 16 (93.8%) facilities in North America revealed that standardised disinfection protocols have been developed and regularly practised. One of the main issues concerning disinfection in aquaculture is accounting for disinfection efficiency. For example, it is very common that producers follow the recommended dose and application strategy described by the supplier; however, although this is a practical approach, there are multiple factors that might influence pre-defined protocols, including the type of materials, strengths of trade products, and environmental conditions (e.g., temperature and humidity). Hence, validation is sometimes necessary, especially when one is developing a set of standard protocols for a particular production site. Facilities that signified the presence of standardised disinfection protocols in-house were then asked whether these had been experimentally validated (i.e., the protocols had been checked by the responsible employee through a series of tests, to determine the efficiency of disinfection). Five out of the six (83.3%) Norwegian respondents answered that their protocols had not been experimentally validated. The North American counterparts likewise reported 12/15 (80%) facilities with protocols that had not been experimentally validated. Experimental validation of protocols at each site would result in a much higher confidence for the strategy in place and would facilitate a structured approach when refinement and recalibration are to be performed, with previous protocols serving as a reference. There are several approaches for performing experimental validation of disinfection protocols, e.g., (i) testing different concentrations and exposure durations using the recommended protocol from the supplier as a point of reference; (ii) evaluating the impacts of different factors (e.g. cleaning, material quality) on disinfection efficiency; and (iii) quantifying disinfection efficiency either by traditional culture-dependent techniques (e.g. direct plate count) or rapid microbial activity evaluation (e.g. Adenosine triphosphate (ATP) techniques, Bactiquant®-surface). The general absence of protocol experimental validation was perhaps reflected when facilities were asked about their confidence in the sufficiency and effectiveness of their current disinfection practices: 89% of the Norwegian respondents answered "not sure", while only one facility replied "yes" (i.e., confident with the protocol in-place). Much higher confidence was reported by the North American respondents, where approximately 60% responded "yes" to the same question. It is interesting to note, however, that more than 80% of the respondents in both regions reported a protocol compliance rate of between 90 and 100%. This demonstrates that despite some degree of uncertainty in the protocol, the production staff were aware of the importance of disinfection in maintaining the biosecurity measures in the facility. This is further discussed below.

The disinfection protocols from Norwegian respondents (5/6) were mainly 4–10 years old, and only one had a protocol < 3 years old. Many of the land-based RAS facilities in Norway were constructed less than 10 years ago, and the responses reflect this reality. In North America, the age of the protocols (including all the revisions) appeared to be varied: 40% (6/15) were < 3 years old, 3.33% (5/15) were 4–10 years old, 13.3% (2/15) were > 10 years old, and 13.3% (2/15) of the respondents were uncertain of their protocol's age. All surveyed Norwegian facilities reported conducting regular appraisals of their disinfection protocols, although it is unknown how frequently these appraisals are carried out. Because the majority of these facilities are relatively young, the regular appraisals indicate that there is continuous development in these facilities. Comparatively, around 73.3% (11/15) of the North American respondents revealed that they have regular protocol appraisals, and that 73.3% (11/15) have had protocols revised in the previous 3 years.

Record-keeping of disinfection activities is vital for tracking and accounting production practices, and allows for documenting items such as disinfection frequency, standard approaches, and any specific deviations from these approaches. This information is not only important for logistics, but also crucial should protocol appraisal or revisions be made. Seven out of the nine (77.8%) Norwegian facilities reported keeping records of all routine disinfection in the facility. By comparison, among the North American counterparts only 56.3% (9/15) reported maintaining records of their disinfection practices, and it was unclear why more respondents did not maintain disinfection records.

The second part of the questionnaire dealt with chemical disinfectants being used in the surveyed facilities. Respondents were asked to select which of the six disinfectant groups commonly used in aquaculture are being used in their facilities (Fig. 1A). All facilities in both regions used multiple disinfectants, and even within an individual company, a significant variability existed. This information protocol offers additional insight into the data on the existence of standardised protocol at each RAS facility discussed above, in that protocols are apparently farm-specific rather than company-wide. In Norwegian facilities, peracetic acid (PAA) and chlorine were the two most common disinfectants, with PAA as the most frequently cited (8/9 of the facilities reported using PAA). Quite a different profile was identified in North America, where the most frequently cited disinfectant was chlorine/sodium hypochlorite, followed in popularity by formalin and quaternary ammonium compounds. Furthermore, some facilities in North America reported that they are also using Virkon, alcohol, sodium hydroxide, and sodium chloride. Although none of these has been specified by the Norwegian counterparts, we can assume that alcohol is also used at Norwegian facilities based on common knowledge and previous site visits. Though it is quite difficult to pinpoint a specific reason for such a striking difference, we consider that the substantially higher number of PAA-based trade products approved in Norway (compared to chlorine-based agents) offers a reasonable explanation for this observation.

The Norwegian Food Safety Authority (Mattilsynet) is the national governing body responsible for ensuring that food and drinking water are as safe as possible for consumers in Norway. Mattilsynet has identified several disinfectants that are approved for use in aquaculture in Norway, including ADDI Aqua, Aqua Des, AquaZone, Grotanol 3025, Hygi-Des, Kick-Start, NORMEX Desinfecta, Perfectoxid, Redoxzon, Salar Des, VigorOx A&F 5%, Vigorox A&F 15%, and Virocid (https://www.mattilsynet.no/fisk_og_akvakultur/akvakultur/desinfeksjon/godkjente_desinfeksjonsmidler_i_akvakultur.802). This list is valid for the time period when the survey was conducted; however, several products have already been listed since then (refer to the link provided for a complete, up-to-date list). Perfectoxid (71.4%) was the most commonly used disinfectant in the surveyed facilities, followed by Virocid (42.9%) and ADDI Aqua (28.6%). Perfectoxid and ADDI Aqua are peracetic acid-based disinfectants, and this result corroborates the general profile (Fig. 1A) that PAA is commonly used in the surveyed Norwegian RAS facilities. PAA is a strong oxidant that is commercially available in an equilibrium mixture with acetic acid, hydrogen peroxide, and water (Pedersen et al., 2009), and is highly regarded because of its efficacy at low doses, rapid decay, and absence of toxic residuals (Pedersen and Lazado, 2020).

The respondents were then asked what criteria were used to select disinfectants to be used in the facility. We provided them ten fundamental criteria (Fig. 1B) to rate and, interestingly, both the Norwegian and North American producers agreed that efficacy against pathogens is the universal criterion valued most when selecting a disinfectant. Even though many of these facilities did not have experimentally validated protocols, the prioritisation of this criterion might partly reflect the considerable trust they give to the recommended usage protocol from the supplier. The Norwegian respondents valued user safety as equally as efficacy, followed by ease of application, nature of the items to be disinfected and the potential for damage and threats of residuals. For the North American counterparts, efficacy against pathogens was followed by user safety, threats of residuals, effective concentration, exposure time, and availability.

The third part of the questionnaire explored disinfection related to specific aspects of production in RAS, which were divided into tanks, pipelines, floors, and ancillary equipment (Table 2). Forty percent of the Norwegian RAS facilities answered that they are disinfecting tanks and pipelines after every production cycle, while around 62.5% of the North American facilities are doing the same. Cleaning is a pre-disinfection practice that allows the removal of algae, biofilms, faeces, and any leftover feeds in the system (OIE, 2003). While the Norwegian responses were somewhat sparse (only 40% responded when asked if they perform cleaning prior to disinfection), most (93.8%) of the North American respondents reported practising cleaning before disinfection. In both geographic regions, the universal strategy for cleaning included the use of high-pressure sprayers, mechanical scrubbing, or a combination of both. Only two Norwegian facilities responded that they considered the construction material in the selection of disinfectant, whereas 69% of respondents from North America take this consideration into account.

Hydrogen peroxide was the most common disinfectant for tanks in Norwegian facilities, with five respondents indicating its use at their production sites. On the other hand, chlorine/sodium hypochlorite was identified to be the most predominant tank disinfectant among North American respondents (9/16). When performing tank disinfection in Norwegian facilities, the most common (8/9) strategy reported was spraying the disinfectant directly onto the tank surface. One facility responded, however, that they fill a given tank with water and then add the disinfectant to the water column and allow for a certain contact time. Unlike in Norwegian facilities, the North American counterparts reported relatively equal frequency in adopting direct spraying of disinfectant and adding a disinfectant to the water column as means to disinfect the tanks, with several facilities reporting both methods being used. While chlorine/sodium hypochlorite was the predominant

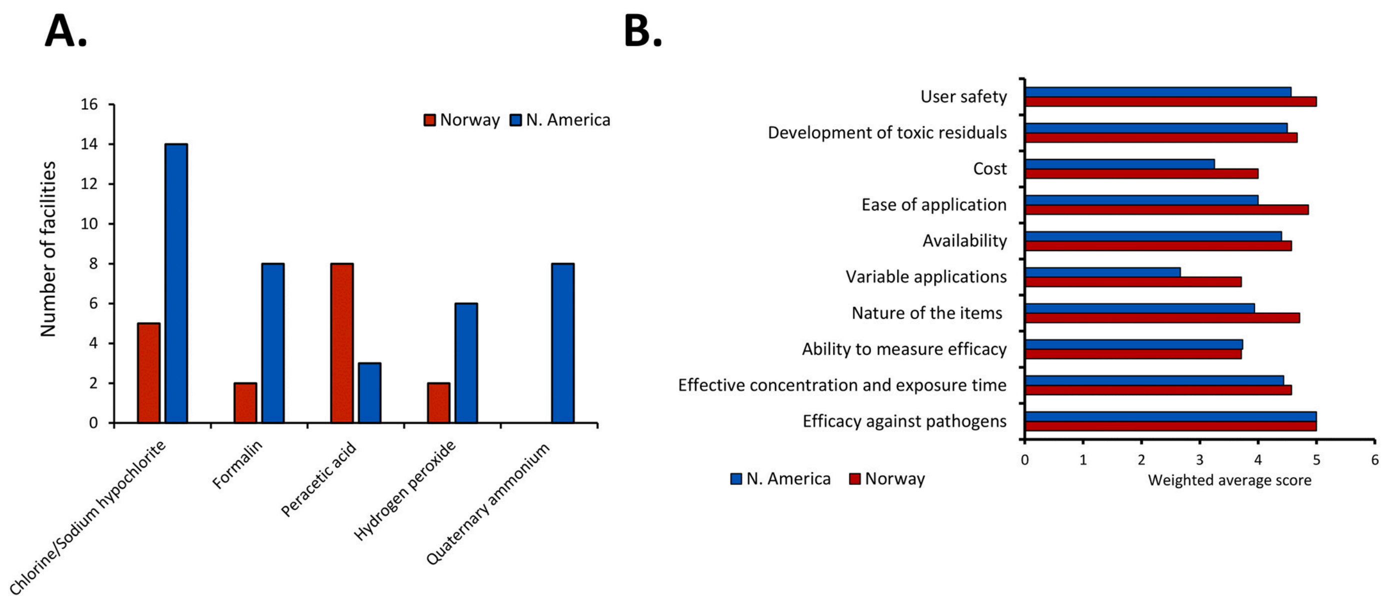

Fig. 1. Summary of chemical disinfectants in use (A) and the criteria in the selection of disinfectants and their weighted average scores (B).

disinfectant for pipelines in North America, no clear inclination towards a specific disinfectant was identified from the surveyed Norwegian facilities. Besides the choices provided, sodium hydroxide is also used in North America to disinfect tanks (4/15) and pipelines (5/15). When we further asked about the method for pipeline disinfection, only one Norwegian respondent provided an answer, specifying that this is carried out by direct spraying of disinfectant to the pipeline. Most of the respondents in North America (11 out of 15 practising pipeline disinfection) reported using a reservoir tank and pumping disinfectants through the systems to disinfect pipelines. In both tank and pipelines, the contact time reported by all Norwegian facilities was between 12 and 24 h, while in North America disinfectant contact time for tank and pipelines was more variable among responding facilities: 2/13 for a minimum of 1 h; 4/13 for > 1–12 h; 5/13 for > 12–24 h; and 2/13 reporting contact times > 1 day. Additionally, all facilities reported rinsing with water after disinfection. Only 1/9 facilities in Norway reported having a set of criteria to assess that cleaning, disinfection, and rinsing have been done properly. On the other hand, 9/14 facilities in North America reported having a set of criteria for all these processes for the tank and pipeline disinfection. This apparent difference suggests that the disinfection strategies in place were relatively more structured in the surveyed North America facilities than their Norwegian counterparts, and although the sample size was small the responses are likely indicative of general industry trends. This might be related to the fact that many of the North American facilities have been in operation for longer than the Norwegian facilities. When asked about how soon they re-stock the disinfected tanks with fish, only five Norwegian respondents provided an answer: one answered 1 day after disinfection, while four facilities allowed 1 week to pass before stocking. A similar tendency was collated from the North America facilities: only two facilities reported 1 day after disinfection and the remaining facilities reported at least 1 week being allowed to pass before re-stocking.

Although floors are areas that do not normally come into direct contact with fish during the culture period, they may still be reservoirs for opportunistic pathogens, and therefore floors are critical sites that must be considered in RAS facility disinfection strategies. Five out of nine Norwegian facilities perform floor disinfection, and disclosed that cleaning (i.e., removal of sediments, biofilms, dirt, primarily with a high-pressure water hose) is conducted prior to performing this practice. From these five facilities, three conduct floor disinfection on a weekly basis, while the other two only carry this out when necessary. Most (13/15) responding facilities in North America perform floor disinfection, and among these, 12/13 perform cleaning prior to disinfection. In terms of frequency, 3/15 facilities disinfect on a weekly basis, while the remaining 12 carry out floor disinfection only when necessary. Peracetic acid and hydrogen peroxide are both used for floor disinfection in surveyed sites in Norway, with a contact time between 1 and 24 h. In North American facilities, chlorine/sodium hypochlorite and quaternary ammonium compounds are most frequently cited, with most facilities reporting a contact time of 1 to 12 h. Rinsing after disinfection is a common practice (4/5) in Norwegian sites, while the North American facilities were generally split as to whether floor rinsing with water is carried out. The choice to perform rinsing after disinfection is perhaps related to the disinfectant in use, as some trade products are available rinse-free. There was a consensus from the Norwegian facilities in the absence of identified criteria to assess the efficiency of cleaning, disinfection, and rinsing of the floor. In comparison, North American sites were generally split regarding having a disinfection assessment protocol, and it was unclear which factor(s) were being considered at those sites that carried out disinfection

Table 2
Disinfectants used in different aspects of the production system from the surveyed facilities. Note that some facilities are using more than one of the disinfectants.

	Norway				North America			
	Tanks	Pipelines	Floor	Ancillary	Tanks	Pipelines	Floor	Ancillary
Chlorine/Sodium hypochlorite	1	3	0	0	9	10	5	9
Formalin	1	3	0	0	1	2	0	0
Peracetic acid	3	3	7	7	1	1	1	1
Hydrogen peroxide	5	3	5	6	3	4	3	2
Quaternary ammonium	0	2	0	0	3	1	5	6

assessments.

Ancillary equipment are materials and equipment that support day-to-day activities at production facilities. Ancillary equipment might include nets, buckets, transport material, boots, ladders, and ear protection, among many other items. These are not only potential pathogen reservoirs but can also serve as vectors for opportunistic pathogens. At least six of the Norwegian facilities are using both peracetic acid and hydrogen peroxide in the disinfection of most of their ancillary equipment. Seventy percent ethanol (i.e., sprays or wipes) is used for small equipment and for those with specific handling requirements (e.g., probes). Six of nine facilities use different disinfectants for different ancillary equipment, and use a specific cleaning/disinfection protocol for separate ancillary equipment items. When asked about the frequency of disinfection, two respondents answered daily, one answered monthly, and two answered after every use. Three respondents answered that they do not have a routine procedure in place, and that they conduct ancillary equipment disinfection only when necessary. These results reflect the overall variability in ancillary equipment disinfection, but it must be emphasised that frequency of disinfection might vary depending on the type of ancillary equipment. The survey did not request details regarding the particular approach for specific ancillary equipment. Similarly, with floor disinfection, chlorine/sodium hypochlorite and quaternary ammonium compounds were the common disinfectants in North America for ancillary equipment. Virkon, a disinfectant that contains oxone, sodium dodecylbenzenesulfonate, sulfamic acid, and inorganic buffers, was reported to be in use by at least eight respondents. Most facilities use more than one disinfectant based on which particular ancillary equipment is being treated. When asked about the frequency of disinfection, North American respondents (15) answered: after every use (9), daily (2), weekly (1), no routine procedure (3).

Disinfection is first and foremost an integral aspect of biosecurity measures, where the main objective is to prevent the occurrence of disease, and secondarily, to control pathogen transmission should there be a disease outbreak. The final part of the questionnaire explored disease outbreaks in the surveyed facilities. Only one of the surveyed sites in Norway reported experiencing disease outbreaks in the last 5 years. Although this facility encountered bacterial, viral, and parasitic diseases, the majority ($>$ 70%) of outbreaks were associated with viral pathogens. The respondent did not indicate the specific nature of the outbreaks; however, it was revealed that when outbreaks occurred, disinfection was carried out immediately, and the strategy followed the facility's routine disinfection protocol. Out of the 14 facilities from North America that completed this section, five had experienced disease outbreaks in the last 5 years. No viral agents were listed as being associated with the outbreaks, which were predominantly (4/5) bacterial in origin, with *Vibrio* spp., *Yersinia ruckeri*, and *Aeromonas salmonicida* being specified. The remaining facility reported a mix of bacterial and parasitic agents (no pathogens specified). In the event of an outbreak, disinfection was carried out immediately by 4/5 facilities, and 4/5 facilities reported that the disinfection strategy during outbreaks was similar to the routine protocols.

Finally, all respondents from both regions disclosed that their staff undergo training to perform disinfection at their facilities. This supports the high compliance rate discussed above and further highlights the importance of providing staff with the necessary knowledge for effective disinfection, in order to carry out practices that are essential for optimal biosecurity. Both regions were in agreement on the importance of protective gear in performing some targeted disinfection, and both followed established occupational safety guidelines (i.e., Norway: Helse, Miljø og Sikkerhet – HMS protocol; North America: OSHA, HACCP). Many of the disinfectants are available in concentrated forms, which are toxic, corrosive, and flammable; therefore, proper protective gear must be worn during handling. Appropriate use of masks (e.g. N96), goggles and chemical-resistant gloves (e.g. nitrile, neoprene, polyvinylchloride, polyvinylalcohol) provides protection for the individual handling the disinfectant. The Material Safety Data Sheet of the disinfectant discloses the type of protective gear and the conditions that must be considered during handling and use of the specific chemical. The survey managed to acquire information from the respondents that occupational safety guidelines are in place for handling the disinfectants in the facility; however, we were not able to identity the specifics on how these guidelines are practiced and managed.

In conclusion, the survey revealed some interesting information regarding different disinfection strategies currently in use by major land-based RAS salmonid producers in Norway and North America. Some of the key similarities among the facilities between the two regions include: 1) the majority have standardised disinfection protocols, but the disinfection efficiency has not been experimentally validated; 2) the majority of the facilities continually appraise these protocols, emphasising the dynamic nature of their practices; 3) efficacy against pathogens and user safety are the topmost criteria in selecting disinfectants; 4) different practices are used for different ancillary equipment, where the type and requirement of the equipment are considered in disinfection approaches; 5) immediate disinfection is carried out after an outbreak; and 6) staff in the production site are trained to perform disinfection including proper use of protective gear and adherence to specific occupational health guidelines. In terms of differences, 1) most Norwegian facilities do not have a set of criteria in assessing cleaning, disinfection, and rinsing strategies, unlike in the majority of North American sites; 2) peracetic acid and hydrogen peroxide are commonly used surface disinfectants in Norwegian RAS sites while chlorine/sodium hypochlorite and quaternary ammonium compounds are common in North America; and 3) there is significant variability in the practices for disinfecting tanks and pipelines, floors, and ancillary equipment, especially regarding the specific disinfectant, pre- and post-disinfection practices, and contact time, among other things.

Even though the number of sites is limited, the respondents included those from all major salmon companies using RAS technologies, and therefore responses provide a representative snapshot of the current industry scenario. The information presented here is valuable not only for the producers, but also for policymakers and governmental bodies, which can be used as foundational knowledge in benchmarking the disinfection strategies in the hope of establishing a set of universal guidelines, particular for those operating in recirculation aquaculture.

Declaration of Competing Interest

The authors declare no conflict of interest. Mention of trade names in the paper does not imply any recommendation or endorsement by Nofima or The Conservation Fund.

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References

Bentzon-Tilia, M., Sonnenschein, E.C., Gram, L., 2016. Monitoring and managing microbes in aquaculture - towards a sustainable industry. Microb. Biotechnol. 9, 576–584.

Cabillon, N.A.R., Lazado, C.C., 2019. Mucosal barrier functions of fish under changing environmental conditions. Fishes 4, 2.

FAO, 2020. The state of world fisheries and aquaculture 2020. Sustain. Action. https://doi.org/10.4060/ca9229en. (Rome).

Fiskeridepartementet, 2008. Forskrift om godkjenning og bruk av desinfeksjonsmidler i akvakulturanlegg og transportenheter, 2008-0695. https://lovdata.no/dokument/LTI/forskrift/2008-06-17-821 (Norway).
OIE, 2003. Manual of Diagnostic Tests for Aquatic Animals, 4th ed. Office international des épizooties, Paris.
Pedersen, L.F., Lazado, C.C., 2020. Decay of peracetic acid in seawater and implications for its chemotherapeutic potential in aquaculture. Aquac. Environ. Interact. 12, 153–165.
Pedersen, L.-F., Pedersen, P.B., Nielsen, J.L., Nielsen, P.H., 2009. Peracetic acid degradation and effects on nitrification in recirculating aquaculture systems. Aquaculture 296, 246–254.
Romano, N., Sinha, A.K., 2020. 2 - husbandry of aquatic animals in closed aquaculture systems. In: Powell, M.D. (Ed.), Kibenge, F.S.B. Academic Press, Aquaculture Health Management, pp. 17–73.
Summerfelt, S.T., Sharrer, M.J., Tsukuda, S.M., Gearheart, M., 2009. Process requirements for achieving full-flow disinfection of recirculating water using ozonation and UV irradiation. Aquac. Eng. 40, 17–27.
Terjesen, B.F., Summerfelt, S.T., Nerland, S., Ulgenes, Y., Fjæra, S.O., Megård Reiten, B.K., Selset, R., Kolarevic, J., Brunsvik, P., Bæverfjord, G., Takle, H., Kittelsen, A.H., Åsgård, T., 2013. Design, dimensioning, and performance of a research facility for studies on the requirements of fish in RAS environments. Aquac. Eng. 54, 49–63.
Yanong, R., Erlacher-Reid, C., 2012. Biosecurity in Aquaculture, Part 1: An Overview. Southern Regional Aquaculture Center, Florida.
Ytrestøyl, T., Takle, H., Kolarevic, J., Calabrese, S., Timmerhaus, G., Rosseland, B.O., Teien, H.C., Nilsen, T.O., Handeland, S.O., Stefansson, S.O., Ebbesson, L.O.E., Terjesen, B.F., 2020. Performance and welfare of Atlantic salmon, *Salmo salar* L. post-smolts in recirculating aquaculture systems: importance of salinity and water velocity. J. World Aquacult. Soc. 51, 373–392.