

recirculating aquaculture systems (RAS) are obtained at a substantial electrical energy cost, and that reported energy intensities vary widely with system design and species (Badiola et al., 2018). Together, these strands indicate that automation in aquaculture is best understood not as a uniform improvement but as a set of trade-offs between productivity, resource use, capital intensity and operational risk.

Unlike previous discussions, which focus mainly on aquaculture production technologies or on their environmental performance, this review integrates automation, occupational safety and workplace risk management within the specific context of Singapore's local fish production. Occupational safety and health in aquaculture has been characterised internationally as an under-reported area with a hazard profile spanning safety, physical, chemical, biological, ergonomic and psychosocial categories (Lloyd's Register Foundation, 2021), yet it is rarely treated alongside automation adoption in the same analysis. Bringing the two together is the intended contribution of this review, and it is directly relevant to land-scarce, high-regulation urban settings where automation is being adopted quickly and where the workforce composition is changing as a result. This project investigates the safety practices relevant to aquaculture both offshore and onshore. The relevant safety standards for aquaculture are reviewed, and a risk assessment is performed for a typical aquaculture process.

The following are the major tasks of the project.

- 1 Understand the aquaculture challenges and opportunities in Singapore and overseas
- 2 Study and review the process of fish farming
- 3 Conduct a review of safety practice and standards in fish farming
- 4 Conduct a risk assessment for the activities, feeding and harvesting phase

2 Methods

2.1 Review design

This work is a structured narrative review with an applied risk assessment component. It was not registered as a systematic review and does not claim systematic-review status: the evidence base combines peer-reviewed literature with regulatory instruments, national standards and industry documentation, and the latter categories are not indexed in a way that permits exhaustive, reproducible retrieval. The review design was instead structured to be transparent about what was consulted and on what basis material was retained.

The review proceeded in four sequential stages, corresponding to the four tasks stated in Section 1: (i) characterisation of aquaculture challenges and opportunities in Singapore and internationally; (ii) description of the fish farming process and the production systems in use; (iii) review of safety practices and standards applicable to aquaculture work; and (iv) application of a formal risk assessment methodology to two representative activities, feeding and harvesting, in both manual and automated modes.

2.2 Information sources

Three categories of source were consulted.

Peer-reviewed literature. Searches were conducted in ScienceDirect, Scopus and Google Scholar. Search terms were combined from three groups: production system terms ("aquaculture", "fish farming", "recirculating aquaculture system", "RAS", "onshore", "offshore"); technology terms ("automation", "auto-feeder", "Internet of Things", "IoT", "smart aquaculture", "precision aquaculture"); and safety terms ("occupational safety and health", "risk assessment", "hazard", "injury"). Singapore-specific searches additionally used "Singapore" and "30 by 30". Records were screened by title and abstract, and retained records were read in full.

Regulatory and standards material. National and international instruments governing aquaculture practice and workplace safety were consulted directly from the issuing bodies, including the Singapore Food Agency, the Singapore Standards Council, the Ministry of Manpower and the Workplace Safety and Health Council in Singapore, and equivalent bodies in Prince Edward Island (Canada), Malaysia and Western Australia. These sources are not indexed in academic databases and were located through the issuing organisations' own publication registers.