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Safety and Automation in Singapore's Local Fish Production: Opportunities and Challenges for Sustainable Aquaculture Development

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Abstract Singapore aims to increase its local food production to 30% by 2030, with a strategic focus beginning on fish and shrimp production. Challenges from rising labour costs and limited space for sustainable aquaculture present significant obstacles. This process review highlights current technologies for fish sorting and harvesting and assesses the potential for automation in onshore fish farming. It also examines the fish farming process, scrutinises safety practices and standards, and applies a risk assessment framework for selected aquaculture activities, notably for feeding and harvesting activities, and offers insights into the global aquaculture industry, offering a strategic standpoint for increasing local fish production, reinforcing food safety, and support the sustainability of the aquaculture sector. To achieve the 30% local food production target by 2030, Singapore needs to address geographic limitations, supply-chain dependence, labour costs, and energy consumption. Thus, embracing urban environments, ensuring product freshness, and implementing advanced technologies like auto-feeders, IoT, and recirculating systems are important approaches for supporting the expansion of the local aquaculture industry. Alongside these opportunities, this review also considers capital cost, energy intensity, workforce competency, maintenance burden, and cybersecurity exposure as practical constraints on adoption. This review is expected to provide a practical plan to integrating automation technologies, safety management practices, and sustainable production strategies in urban aquaculture development.

Keywords Food safety; Local produce target; Fish farming processes; Automation in aquaculture; Fish farming industry; Onshore fish farming

1 Introduction

Food security concerns and potential disruptions to global supply chains have encouraged Singapore to increase local food production from 10% to 30% by 2030. Fish and shrimp are an important source of this food, but the main challenges are labour cost and the space available for sustainable aquaculture. This study sets out to understand the processes of fish farming and to identify where automation may be applied across breeding, rearing and transportation. A key objective is to identify and understand existing technologies and solutions for fish sorting and harvesting. A third aim is to characterise the onshore fish-farming industry in Singapore, identifying the key players in the aquaculture value chain and the automation opportunities in onshore farming. The research follows a structured approach, beginning with the challenges and opportunities in aquaculture both locally and globally, then examining the fish-farming process, reviewing the prevailing safety practices and standards, and culminating in a risk assessment of two pivotal activities: feeding and harvesting. The insights are intended to strengthen understanding of the aquaculture industry in Singapore and worldwide, and to inform strategies for increasing local fish production, reinforcing food safety and supporting the sector.

Internationally, the aquaculture sector has moved rapidly towards what is variously described as smart, precision or digital aquaculture. Reviews of Internet of Things (IoT)-based smart aquaculture management systems describe sensor networks, software interfacing, artificial intelligence, cloud computing and data storage as the constituent technologies of contemporary farm monitoring, and identify water quality management, feeding behaviour monitoring and animal health surveillance as the dominant application areas (Yadav et al., 2023). Parallel work on the energy performance of land-based systems has drawn attention to the fact that the water-efficiency gains of 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.

Industry and operator documentation. Publicly available descriptions of production systems operated by licensed Singapore farms were used to characterise the technologies in current local use. Two operators were selected as illustrative cases, one offshore and one onshore, on the basis that they are licensed by the Singapore Food Agency, operate at commercial rather than pilot scale, and have publicly documented their production technology. These cases are illustrative of the systems in use and are not presented as a representative sample of the sector.

2.3 Selection criteria

Material was retained where it met all of the following criteria: published in English; directly concerned with aquaculture production systems, aquaculture automation, or occupational safety and health in aquaculture or a closely comparable primary industry; and either applicable to tropical or land-constrained production settings, or providing a standard or framework transferable to such settings.

Material was excluded where it addressed fish biology, genetics, nutrition or disease without reference to production process, workforce or safety; where it concerned capture fisheries rather than aquaculture, except where the occupational safety content was explicitly transferable; where it was promotional material without a verifiable technical or regulatory basis; and where a more recent authoritative version of the same standard or dataset was available.

No formal quality appraisal instrument was applied to individual studies, and no meta-analysis was undertaken. This is a limitation of the review and is discussed in Section 4.7.

2.4 Risk assessment framework

The risk assessment reported in Section 3.5 follows the three-step methodology set out in the Code of Practice on Workplace Safety and Health Risk Management issued by the Workplace Safety and Health Council in Singapore (WSH Council, 2011), supported by the risk management guidance of the Ministry of Manpower (Ministry of Manpower, n.d.). The three steps are hazard identification, risk evaluation and risk control.

Hazards were identified by decomposing each activity into its constituent work steps and classifying the hazards encountered at each step under the categories used in the international aquaculture occupational safety literature: safety, physical, chemical, biological, ergonomic and psychosocial (Lloyd's Register Foundation, 2021). Risk was evaluated using the semi-quantitative matrix specified in the Code of Practice, in which severity and likelihood are each rated on a five-point scale and multiplied to give a Risk Priority Number (RPN), which is then classified as low, medium or high risk. The matrix and classification bands are reproduced in Figure 1.

Risk controls were assigned following the hierarchy of controls, in which elimination and substitution are preferred to engineering controls, engineering controls to administrative controls, and administrative controls to personal protective equipment. Where the risk assessment tables in Section 3.5 record personal protective equipment as an existing control, the additional control column identifies the higher-order measure recommended. Two activities, feeding and harvesting, were selected for assessment because they are performed at high frequency across the production cycle, they occur in both manual and automated modes in Singapore farms, and they involve direct worker interaction with water, live stock and moving machinery.

The risk assessments presented are generic worked examples applied to a representative aquaculture process. They were not conducted at a named facility, and the ratings should be read as illustrative of the method rather than as an audit of any particular farm. A site-specific assessment would be required before the ratings could be relied upon operationally.

Classification of Risk (Risk Matrix)

('RPN' column)

Severity \ Likelihood	Rare (1)	Remote (2)	Occasional (3)	Frequent (4)	Almost Certain (5)
Catastrophic (5)	5	10	15	20	25
Major (4)	4	8	12	16	20
Moderate (3)	3	6	9	12	15
Minor (2)	2	4	6	8	10
Negligible (1)	1	2	3	4	5

Risk level	Risk Acceptability	Recommended Actions
Low Risk	Acceptable	• No additional risk control measures may be needed. • Frequent review and monitoring of hazards are required to ensure that the risk level assigned is accurate and does not increase over time.
Medium Risk	Tolerable	• A careful evaluation of the hazards should be carried out to ensure that the risk level is reduced to as low as reasonably practicable (ALARP) within a defined time period. • Interim risk control measures, such as administrative controls or PPE, may be implemented while longer term measures are being established. • Management attention is required.
High Risk	Not acceptable	• High Risk level must be reduced to at least Medium Risk before work commences. • There should not be any interim risk control measures. Risk control measures should not be overly dependent on PPE or appliances. • If practicable, the hazard should be eliminated before work commences. • Management review is required before work commences.

Severity Scoring

('S' column)

Level	Severity	Description
5	Catastrophic	Fatality, fatal diseases or multiple major injuries.
4	Major	Serious injuries or life-threatening occupational disease (includes amputations, major fractures, multiple injuries, occupational cancer, acute poisoning).
3	Moderate	Injury requiring medical treatment or ill-health leading to disability (includes lacerations, burns, sprains, minor fractures, dermatitis, deafness, work-related upper limb disorders).
2	Minor	Injury or ill-health requiring first-aid only (includes minor cuts and bruises, irritation, ill-health with temporary discomfort).
1	Negligible	Not likely to cause injury or ill-health.

Likelihood Scoring

('L' column)

Level	Likelihood	Description
1	Rare	Not expected to occur but still possible.
2	Remote	Not likely to occur under normal circumstances.
3	Occasional	Possible or known to occur.
4	Frequent	Common occurrence.
5	Almost Certain	Continual or repeating experience.

Figure 1 Risk matrix and classification of risk (WSH Council, 2011)

3 Results

3.1 Aquaculture challenges and opportunities in Singapore and global contexts

According to Funge-Smith and Phillips (2001), there are four types of aquaculture systems (Table 1). Singapore uses water-based systems, traditional and modern coastal net-cage farms and close-containment floating farms, and land-based systems, including tank-based culture, open-pond methods and indoor multi-tier systems (World Aquaculture Society, 2020; Singapore Food Agency, 2022a).

Table 1 Four types of Aquaculture systems

No.	Aquaculture system
1	Water-based systems in cages and pens, found in inshore and offshore settings.
2	Land-based systems: rain-fed ponds, irrigated channels, tanks and flow-through systems.
3	Recirculating aquaculture systems (RAS): enclosed systems and open pond-based recirculation.
4	Integrated farming systems: livestock-fish and combined agriculture-fish systems in farms and irrigation ponds.

Since the pandemic, the island nation has adopted a “30-by-30” target to achieve food security by producing 30% of its nutritional needs by 2030. The two types of aquaculture system used in Singapore are offshore and onshore farming (World Aquaculture Society, 2020). Singapore’s aquaculture industry comprises 110 licensed land- and sea-based fish farms and currently supplies about 10 percent of local fish consumption (Singapore Food Agency, 2022b). Of this, roughly 85 percent comes from marine aquaculture (offshore cage farming) and 15 percent from freshwater aquaculture in inland waterways (Shen et al., 2021). Marine coastal farms are located in the Johor Straits - Punggol, Serangoon/Loyang, Lim Chu Kang and Pulau Ubin producing species such as grouper, seabass, snapper and milkfish (Singapore Food Agency, 2022c); freshwater farms produce Asian seabass, milkfish, grey mullet, snappers, golden pompano, hybrid groupers and shrimp (Shen et al., 2021).

Non-food species fall into three groups: aquaculture feed (microalgae, macroalgae, phytoplankton, zooplankton and other planktonic organisms); ornamentals (fish, corals, shrimp and molluscs); and organisms used in flow-through or recirculating systems to improve marine environmental conditions (Leal et al., 2018). Two main factors limit local production to about 10 percent: limited coastal area and species range, and heavy reliance on global supply chains. To reach the 30% target, Singapore must convert these challenges into opportunities.

3.2 Species for food and non-food farmed in Singapore

The Singapore Food Agency regulates and licenses land- and sea-based farms (Singapore Food Agency, 2022b). Diseased fish represent a commercial risk, and stocks are affected when processes are not robust. The farming cycle for *Lates calcarifer* (Asian seabass) comprises five stages, fertilised egg, larva, fry (juvenile), fingerling and broodstock completed over up to five years; males are typically harvested at about two years and nine months, while females are retained longer to continue the cycle (FAO, 2009; Shen et al., 2021). Offshore, Singapore Aquaculture Technologies Pte Ltd operates floating tank-based farms (a 3,000 m² floating tank) using data- and AI-driven Recirculating Aquaculture Systems (RAS) for disease prevention and performance monitoring (Singapore Aquaculture Technologies, 2022). Onshore, Apollo Aquaculture Group Pte Ltd uses land-based RAS to recycle and reuse water with 24/7 monitoring and control; its modular three-tier design enables high-rise farming and can be dismantled and re-established away from the coastline, including in urban areas (URA Singapore, 2017).

Waste falls into three categories; solid, dissolved and pathogenic (Miller and Semmens, 2002). In a well-managed farm, roughly 30% of feed becomes solid waste (Miller and Semmens, 2002).

3.3 Challenges and opportunities

There are two main reasons for the 10 percent limited aquaculture production contributing to local food supply. Firstly, limited coastal regions and species for farming, second being heavily reliant from global fish food supply chains. Hence to achieve 30% production local food supply, the Island nation recognises Challenges and Opportunities from the current food production environment (Table 2).

3.4 Study and review of the fish farming process

Singapore Food Agency regulates and provides licenses to fish farms both land and sea based in the island nation. The list of licensed farms is available from the Singapore Food Agency (2022b). Diseased fish is a business/commercial risk and fish stocks are impacted when processes are not robust.

Table 2 Description of Challenges and Opportunities

Description of Challenges and Opportunities	
Challenges	Opportunities
Global Supply Chain Issues (Food Security)	Increase Local Fish Production
Limited coastal regions	Utility in Urban Environments
Labour cost and Skilled Workforce	Freshness and Longevity
Energy cost	Deployment of Technologies such as Auto-feeder and Internet-of-Things (IoT), water monitoring systems and Recirculating Aquaculture Systems (RAS)

Fish farming process for Lates calcarifer Asian Seabass comprises 5 cycles completed up to 5 years. Male Asian Seabass is intended for harvest within 2 years and 9 months, and females are kept longer to continue the 5 cycles from Fertilisation of egg, Larva, Fry (Juvenile), Fingerling and broodstock (FAO, 2009; Shen et al., 2021).

3.4.1 Farming system offshore

Two main system types are seen in Singapore’s offshore farming: the 3,000 m² floating tank and the recirculating aquaculture system (Singapore Aquaculture Technologies, 2022). In the Island-nation Singapore Aquaculture Technologies (SAT) Pte Ltd employs smart farming pioneering floating tank-based fish farms with data and artificial Intelligence driven RAS (Recirculating Aquaculture System). Enabling disease prevention and performance monitoring systems for multifactorial data analysis.

3.4.2 Farming system onshore

In Singapore’s onshore farming there are also two systems, the fish transfer pump and the manual feed process (URA Singapore, 2017). Apollo Aquaculture Group Pte Ltd uses a Land-based food fish culture system to prevent disease in fish food. The RAS (Recirculating Aquaculture System) is also used in land-based fish farming operations. The intent is to recycle and reuse water resources, 24-hour monitoring system and control system is used in their farming environments. Innovation is essential and for this company, a prototype modular three-tier farm enables high-rise farming of fish. The modularity of the structure allows it to dismantle and set up a farm away from the coastline even in urban areas.

3.4.3 Waste removal and cleaning

There are three categories; Solids, Dissolvable and Pathogenic Waste (Miller and Semmens, 2002), in an effectively managed farm, approximately 30% of the feed used will become solid waste. Table 3 summarises each waste category and the corresponding cleaning or control approach (Miller and Semmens, 2002).

Table 3 Waste removal and cleaning

No.	Type of waste	Cleaning / control
1	Solid waste from uneaten feed and faeces; if not cleared, becomes total suspended and total dissolved solids.	Rapid capture reduces the dissolved organic load.
2	Dissolved waste (ammonia, nitrite, nitrate, phosphorus, organic matter); un-ionised ammonia, excreted through the gills, is the most toxic form.	Autotrophic bacteria convert ammonia to less toxic forms; providing a large surface area for bacterial growth is the most effective approach.
3	Pathogenic waste; farms can increase potentially pathogenic organisms in effluent.	Chlorination, ultraviolet radiation and ozonation; UV treatment occurs in a chamber and is not harmful downstream.

3.4.4 Review of safety practice and standards in fish farming

Safety standards in fish farming are unique and developed over years of research in global fish farming industries; these standards are non-exhaustive and adapted to the requirements and capacity of localities. There are no specific policies that any one country must adhere to, and each nation would follow their own best practices. The Singapore Standard 670:2021 (Singapore Standards Council, 2021) titled Specification for good aquaculture practice is one example of aquaculture farm production in the Island nation; (a) Food safety and quality; (b) Animal health and welfare; (c) Environmental integrity; and (d) Socio-economic aspects. However, the article does not specify aquaculture occupational health and safety practices intended for this study (Table 4).

Examples of Safety standards used worldwide for aquaculture normative Safety Practice:

Table 4 Safety standards used in aquaculture worldwide

No.	Standard / code of practice	Summary
1	Aquaculture Safety Code of Practice, Prince Edward Island (Prince Edward Island Aquaculture, 2008)	Requires aquaculturists and workers to identify and control hazards; covers safe use of tools and machinery and safe work practices for onshore and offshore operations.
2	Guidelines on Occupational Safety and Health in Fishing and Aquaculture Operations, Malaysia (OSH Act 1994) (Department of Occupational Safety and Health, 2001)	Applies to fishing operations in Malaysia; assists the industry in preventing accidents, injury, disease and death.
3	Aquaculture Industry OHS Code, Western Australia (2002) (Aquaculture Council of Western Australia, 2002)	Requires workplaces to meet statutory requirements under the Marine Act, OSH Act and Fish Resources Management Act; defines responsibilities of licence holders, managers, contractors and operators.
4	Code of Practice for Diving at Work, Singapore (SS 511:2018) (WSH Council, 2021)	Covers offshore diving; not prescriptive but requires proper planning and assessment of diving operations and compressed-air breathing apparatus.
5	Occupational health and safety in the aquaculture industry: a global review (Lloyd's Register Foundation, 2021)	Reviews OHS incident evidence and intervention effectiveness; categorises hazards as safety, physical, chemical, biological, ergonomic and psychosocial.

3.5 Risk assessment for feeding and harvesting activities

The main activities involved in manual and automated aquaculture operations, including feeding, equipment maintenance, and harvesting, are summarized in Table 5.

Table 5 Activities for both onshore and offshore farming

Activity	Manual	Automated
Feeding	Personnel wear non-slip boots and gloves and approach a tank or cage with a container of feed (URA Singapore, 2017).	An auto-feeder, scheduled by personnel, dispenses feed into the tank or cage (Hatchery International, 2021).
Equipment maintenance	Structural design provides pipes, containment tanks, water drainage and recirculating systems (Singapore Aquaculture Technologies, 2022).	Machinery includes feed dispensers, material conveyors, RGB cameras for movement and disease monitoring, close-containment tanks and water-quality sensors (Singapore Aquaculture Technologies, 2022).
Harvest	Personnel wear non-slip boots and carry containers to pick and place live fish stock (Singapore Aquaculture Technologies, 2022).	A conveyor transfers live fish stock while fresh water cleans the fish (Farm-Futurism, 2022).

Risk management According to the Code of Practice on Risk Management:

The steps in Hazard Identification, Risk Evaluation and Risk Control specify the methodology and requirements of this Code of Practice (WSH Council, 2011). Severity, likelihood, Risk Priority Number and the classification of risk are shown in Figure 1. The resulting assessments for manual feeding and harvesting are presented in Table 6 and Table 7, and for machinery-assisted operations in Table 8 and Table 9. Severity, Likelihood, Risk Priority Number and Classification of Risk is found with the infographics (Figure 1) followed by the Risk Assessment Form (Ministry of Manpower, n.d.).

Table 6 Risk assessment for manual feeding activities in aquaculture

Company	NA
Conducted by (name, designation, date)	Y. van Ram Sri, Researcher, 20 Aug 2026
Process / location	Manual feeding in aquaculture
Approved by (name, designation, date)	Sri Yahweh van Ram, Researcher, 20 Aug 2026
Last review date	NA
Next review date	20-Jul-29

Table 7 Risk assessment for machinery-assisted aquaculture operations

No.	Work activity	Hazard	Possible accident / ill-health & persons at risk	Existing risk control	Risk (S × L = RPN, level)	Additional risk control	Action officer
1	Transporting fish feed	Ergonomic; lifting heavy loads	Soft-tissue injury (sprains, strains); operations staff	Train on proper lifting technique; strength training	3 × 3 = 9 (Medium)	Distribute load by dividing the weight	Operations Manager
2	Fish feeding	Physical; slippery/moist floor (slip, trip, fall)	Fractures and dislocated joints; operations staff	PPE non-slip boots; ventilators	3 × 2 = 6 (Medium)	Regular maintenance and inspection of premises	Operations Manager (on-going)
3	Fish feeding	Ergonomic; prolonged standing, repetitive strain	Soft-tissue injury (sprains, strains); operations staff	Adequate lighting; distribute load	3 × 3 = 9 (Medium)	Worker rotation; lifting-technique training	Operations Manager (on-going)
4	Fish feeding	Biological; inhalation of pathogenic wastewater	Legionella pneumophila infection; operations staff	Service ventilators every 6 months with anti-bacterial wash	2 × 4 = 8 (Medium)	Engineering control of aerosol generation at source; quarterly antibacterial treatment	Operations Manager
5	Storage of fish feed	Biological; contamination of feed	Diseased livestock; damaged goods	Dry, clean storage; monitor feed expiry	3 × 3 = 9 (Medium)	Monthly maintenance of storage facility	Operations Manager (on-going)
6	Shelving and storage of feed	Physical; falling object (feed container)	Head injury, potentially fatal; operations staff	Safety harness; protective helmet	4 × 2 = 8 (Medium)	Regular inspection; keep feed within designated shelving	Operations Manager
7	Harvesting	Needle-stick objects and sharp teeth	Incised/puncture wound, laceration, infection; harvesting staff	Cut-resistant gloves; adequate lighting	3 × 3 = 9 (Medium)	Handling tools to avoid direct hand contact; worker rotation	Operations & Admin Manager (on-going)
8	Transporting the harvest	Ergonomic; lifting heavy loads	Soft-tissue injury; operations staff	Train on lifting technique; strength training	3 × 3 = 9 (Medium)	Distribute load by dividing weight	Operations Manager
9	Transporting the harvest	Physical; slippery floor (slip, trip, fall)	Fractures and dislocated joints; operations staff	PPE non-slip boots; ventilators	3 × 2 = 6 (Medium)	Regular maintenance and inspection	Operations Manager (on-going)

Table 8 Risk assessment information for machinery-assisted aquaculture operations

Company	NA
Conducted by (name, designation, date)	Y. van Ram Sri, Researcher, 20 Aug 2026
Process / location	Machinery used in the aquaculture farming system
Approved by (name, designation, date)	Sri Yahweh van Ram, Researcher, 20 Aug 2026
Last review date	NA
Next review date	20-Jul-29

Table 9 Risk assessment matrix for machinery-assisted aquaculture operations

No.	Work activity	Hazard	Possible accident / ill-health & persons at risk	Existing risk control	Risk (S × L = RPN, level)	Additional risk control	Action officer
1	Feeding with a pre-programmed automated machine	Machine malfunction scatters feed → slip, trip, fall	Head injury, incised/puncture wound, laceration, infection; operations engineer	Emergency-stop button; dispenser maintenance; reset and re-upload programme	3 × 3 = 9 (Medium)	Containment of dispensed feed at the discharge point; adequate lighting; feed monitoring	Operations Manager (monthly)
2	Harvesting: transfer-conveyor machine	Hand caught in conveyor while removing fish material	Amputated phalanges, crushed bones, joint dislocation; harvesting staff	Safety cage; emergency-stop button; safety signage	3 × 2 = 6 (Medium)	Interlocked guarding and lockout–tagout procedure for clearing blockages; safe entry procedure	Area Manager (on-going)

4 Discussion

4.1 Safety management as an enabler of automation

The thirty-by-thirty vision to expand local fish production must account for the present-day cap of 10 percent of the existing fish production and possible fluctuating percentages where fish stock may be diseased, amounting to losses in farmed production and total output. Therefore, in order to revive the industry, the deployment of safe work practices through the study of aquaculture production processes are the enablers to enrich the workforce and prevent safety hazards from occurring in offshore and onshore aquaculture workplaces. The international aquaculture safety standards provide a lens into the aquaculture occupational health and safety practices from Prince Edward Island, Malaysia, Western Australia, Lloyd's Register Foundation and diving code of practice from Singapore. Code of practice is instrumental when conducting risk assessments for offshore and onshore aquaculture processes from manual labour to machine aided automated feed and harvest processes.

4.2 Economic barriers to adoption

The capital intensity of automated systems is a substantial barrier, particularly for the smaller operators that make up much of Singapore's licensed farm population. Multi-tier land-based facilities and instrumented floating tank systems require capital outlay well beyond that of traditional net-cage operations, and the payback period depends on sustained production volume and price realisation that a small operator may not be able to guarantee. Where automation is adopted incrementally, integration cost between subsystems supplied by different vendors becomes a further expense that is frequently underestimated at the planning stage. The technologies described in this review may therefore support productivity and sustainability gains, but the conditions under which those gains are realised are specific and are not met by every operator.

4.3 Energy consumption of recirculating systems

RAS delivers marked reductions in water exchange, but at a significant electrical energy cost. Reported energy intensities vary widely across published studies, reflecting differences in species, system scale, thermal regulation requirements and boundary definitions (Badiola et al., 2018). Water circulation and thermal control consistently account for the largest share of demand. For Singapore, where electricity is generated predominantly from imported natural gas, this energy intensity has direct implications for both operating margin and the carbon footprint of locally produced fish. A production target expressed in volume terms does not offer a guarantee to environmental improvement over imported products; the comparison depends on the energy profile of the production system and the emissions intensity of the electricity supply.

4.4 Technical workforce requirements

Automation changes the composition of the aquaculture workforce as well as its size. Instrumented systems require competencies in sensor calibration, control system operation, data interpretation and mechanical maintenance that are not typically present in a workforce trained for manual husbandry. The occupational safety consequence is significant: a worker who does not understand the control logic of an automated feeder is poorly placed to recognise abnormal operation, and a worker who has not been trained in energy isolation is at elevated risk when clearing a conveyor. Competency requirements should therefore be treated as an integral part of automation planning rather than as a downstream training matter, and safe operating procedures should be developed in parallel with system commissioning rather than after it.

4.5 Maintenance and system reliability

Highly automated closed systems concentrate dependency on a small number of critical subsystems. Failure of circulation, oxygenation or biofiltration in a densely stocked RAS can produce rapid stock loss, which represents both a commercial risk and a stressor on staff responding to the event. Maintenance access is itself a hazard-generating activity: the entanglement and crush risks identified in Table 7 arise principally during clearing and servicing rather than during normal operation. Reliability planning, including redundancy of critical plant, alarm escalation and defined out-of-hours response, is accordingly a safety matter and not solely a production matter.

4.6 Cybersecurity of IoT-based systems

Where feeding, aeration and water quality control are network-connected, the integrity and availability of the control network become determinants of both stock survival and worker safety. Unauthorised modification of a feeding schedule or a setpoint, or denial of access to monitoring data, could produce consequences equivalent to a mechanical failure. Sensor networks in aquaculture are frequently assembled from heterogeneous commercial components with varying security maturity, and are often deployed in physically exposed locations where device access cannot be tightly controlled. Segmentation of control networks from general business networks, authenticated access to setpoint changes, logging of control actions, and a documented manual fallback procedure are reasonable baseline measures. This intersection between process safety and information security is under-addressed in the aquaculture literature relative to its potential consequence.

4.7 Limitations of this review

Several limitations should be noted. The review is narrative rather than systematic; no protocol was registered, no formal quality appraisal instrument was applied, and the inclusion of regulatory and industry material means that exhaustive reproducible retrieval was not possible. The evidence base is drawn from secondary sources, and no farm-level operational or injury data were collected; the risk assessments presented are generic worked examples of the method rather than site-specific assessments. Aquaculture occupational injury data are in any case sparse and inconsistently reported internationally, which constrains any quantitative claim about the safety effect of automation. Finally, English-language restriction may have excluded relevant regional material, particularly from Southeast Asian producers whose operating context is closest to Singapore's. These limitations indicate the value of future work based on primary farm-level data, including operational energy use, injury and near-miss reporting, and structured comparison of hazard profiles before and after automation at the same facility.

5 Conclusion

There remain limited aquaculture safety publications relating to Singapore. This review indicates that automation technologies, including automated feeding systems, IoT-based monitoring and recirculating aquaculture systems, offer meaningful opportunities for strengthening Singapore's local fish production and for progressing towards the 30-by-30 target. Realising these opportunities depends on the coordinated management of the constraints identified: capital cost, energy consumption, workforce competency, maintenance and reliability, and the cybersecurity of connected control systems. Automation does not remove occupational risk from aquaculture work; it redistributes it, concentrating on a smaller number of higher-consequence hazards among technical staff while reducing the distributed ergonomic and biological burden on manual workers. Integrating automation with sustainable production strategies and with a risk management approach grounded in an established code of practice will be essential for achieving long-term aquaculture development goals.

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Author contributions

Yahweh Van Ram Sri conceived and designed the study, performed the literature review and risk assessment, prepared all tables and figures, and wrote the manuscript.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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