

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 ($S \times L$ = 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	$3 \times 3 = 9$ (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	$3 \times 2 = 6$ (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