

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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