

nitrogen, nitrite, turbidity, conductivity, and other parameters, and combining these tools with intelligent aeration, remote warning, and data analysis platforms, continuous monitoring and precise regulation of pond environments can be achieved. IoT-based freshwater recirculating aquaculture systems (RAS) and pond systems can rely on physical, network, and logical architectures, using edge or fog computing devices, secure communication, databases, and intelligent analytics to monitor key variables such as dissolved oxygen and pH, and to drive actuators such as aerators, water pumps, and feeders for closed-loop control (Hala et al., 2024).

Advanced control methods can further improve management precision and system robustness. For example, fuzzy logic systems that integrate multiple sensors with cloud platforms can autonomously maintain appropriate dissolved oxygen, salinity, and pH levels and have demonstrated high accuracy and stability in real pond trials. Intelligent analytical methods, such as M5 model trees, random forests, and technologies for fish tracking, counting, and behavior analysis, can also improve the prediction of key water quality parameters, feeding regulation, and health warning, providing a foundation for unified monitoring standards and evaluation protocols (Bernal-Higuita et al., 2023). Therefore, the standardization of ecological food chain closure should be advanced together with digital platforms, incorporating best practices, monitoring indicators, and data models into technical guidelines for freshwater aquaculture to improve the stability and replicability of model promotion.

7.3 Constructing a coordinated evaluation system for ecological and economic benefits

The promotion of ecological food chain closure aquaculture should not emphasize ecological value alone; instead, a comprehensive evaluation system that integrates ecological, production, economic, and social benefits should be established. In terms of ecological benefits, priority should be given to evaluating water quality improvement, nitrogen and phosphorus reduction in tailwater, sediment remediation effects, reduced drug use, changes in greenhouse gas emissions, and resource utilization of aquaculture wastes. In terms of production benefits, attention should be paid to survival rate, growth rate, yield per unit area, feed utilization efficiency, disease incidence, and multispecies comprehensive output. In terms of economic benefits, facility investment, labor costs, energy costs, management costs, product prices, overall returns, and long-term maintenance expenses should be comprehensively calculated. In terms of social benefits, employment creation, food safety, green product supply, and the sustainable development of aquaculture communities should also be considered.

Ecological-economic evaluation studies have shown that, when Δ DPSIR, emergy analysis, and cost-benefit analysis are used to compare monoculture with IMTA, IMTA can simultaneously reduce nitrogen emissions, greenhouse gas emissions, and external resource harvesting, while moderately increasing farm profits. When public environmental benefits are monetized, total benefits are much higher than the increase in private profits (Knowler et al., 2020; Nobre et al., 2010). Comprehensive indicators such as emergy-based sustainability indices, environmental sustainability indices, and relative coefficients can also quantify trade-offs among resource use, environmental load, and economic returns, and identify better models among alternatives. In practical promotion, attention should also be paid to the value transformation of ecological products and the standardization of evaluation methods. Ecological food chain closure aquaculture can improve the culture environment, reduce dependence on pharmaceuticals, lower tailwater pollution, and enhance aquatic product quality. These advantages need to be transformed into economic returns through brand building, quality certification, green product labels, eco-labeling, and marketing.

For large-scale aquaculture bases, production records, water quality monitoring records, tailwater treatment records, and product traceability systems can be established to enhance product credibility and market recognition. For local specialty aquatic products, ecological aquaculture models can be combined with regional branding, recreational fisheries, and agricultural tourism to expand industrial value-added space. Broader reviews and meta-analyses have pointed out that current life cycle assessment of IMTA systems still faces methodological challenges, including the selection of functional units, data gaps, and inconsistent impact categories. Therefore, it is necessary to establish aquaculture-specific databases and unified life cycle assessment protocols to improve the comparability of different studies and aquaculture models (Hala et al., 2024). A global systematic review of