

models. This transition is important because computational systems are increasingly expected not only to describe farm status but also to generate predictive, real-time decision support for more efficient and sustainable production.

A second advance is the growing use of hybrid computational architectures that combine sensing, simulation, and machine learning to improve prediction under dynamic farming conditions. AIoT reviews now identify smart feeding, biomass estimation, growth estimation, automation, and water-quality management as core application domains, while newer studies highlight digital twins, federated learning, and other next-generation tools for predictive control and process optimization. Together, these developments show that aquaculture analytics is moving toward connected, adaptive systems rather than isolated statistical models, with increasing emphasis on scalability and resilience across diverse environments.

In production management, the strongest practical applications are in feeding control, water-quality monitoring, and autonomous farm supervision. Smart aquaculture systems can now integrate real-time sensing with predictive models so that fishpond conditions are monitored remotely, growth can be forecast from multiple system parameters, and autonomous feeding can reduce leftover feed. Reinforcement-learning control in recirculating aquaculture extends this further by optimizing feeding rates together with water-quality management, improving tracking accuracy, reducing feed consumption, and increasing long-term system stability compared with conventional control methods.

Commercial and field-oriented reviews also indicate that AI-based management delivers measurable operational benefits when deployed at farm scale. Reported applications include automated and adaptive feeding schedules, early disease detection, biomass estimation, and predictive resource management, with commercial systems showing feed-cost reductions, lower mortality, and improved compliance with environmental standards. More broadly, AI-assisted farm management improves resource efficiency, reduces labor demands, and supports better decisions on fish health, nutrition, and product quality, which makes computational tools increasingly relevant to everyday aquaculture operations rather than only experimental settings (Ragab et al., 2024).

Future research should focus on making computational aquaculture models more transferable, data-efficient, and interoperable across species and production systems. The most consistent priorities are multimodal data fusion, edge computing, lightweight model design, synthetic data generation, and digital twin-based virtual farming, all of which aim to address persistent problems in real-time performance, generalization, and limited labeled datasets. Other reviews reach the same conclusion from a deployment perspective, arguing that broader geographic datasets, standardized data-collection protocols, and integrated AI frameworks are necessary if predictive systems are to become more robust and comparable across studies and farms.

A second priority is ensuring that future innovation remains economically and socially deployable, not only technically advanced. Several recent reviews emphasize that high implementation costs, infrastructure gaps, regulatory constraints, and the digital divide still limit adoption, especially in small-scale and resource-constrained settings. Accordingly, the most promising direction is the development of scalable, adaptive, and standardized AI systems that combine IoT, edge intelligence, blockchain, or robotics where useful, while remaining practical enough to support sustainable aquaculture growth and global seafood security.

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