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Smart Fish Farms: The Rise of AI-Driven Aquaculture

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Aquaculture has emerged as the world's fastest-growing food production sector, yet it faces persistent challenges related to disease outbreaks, resource inefficiency, and environmental degradation. Artificial intelligence (AI), integrated with the Internet of Things (IoT), is transforming traditional fish farming into smart, data-driven systems capable of real-time monitoring, predictive management, and automated decision-making. This article synthesizes recent research on AI-driven aquaculture, covering intelligent water quality monitoring, precision feeding systems, disease detection, biomass estimation, and risk management frameworks. By drawing exclusively on verified open-access scientific literature, the article presents AI-driven aquaculture as a multi-dimensional technological revolution that can enhance productivity, improve fish welfare, and support the global transition toward sustainable blue economies.

Introduction

The aquaculture industry is growing rapidly and is the fastest-growing food industry in the world, with production expanding 16-fold between 1985 and 2018, according to the Food and Agriculture Organization (Theodorou, 2026). Aquaculture plays a vital role in global food security, and by 2030, it is projected to account for more than half of all global fish production (Huang and Khabusi, 2025). However, despite this significant expansion, the sector operates in an environment of high uncertainty, as the management of biological and environmental risks is critical to its sustained growth (Theodorou, 2026). Traditional fish farming practices are labor-intensive and are confronted by serious challenges, including disease outbreaks, high feed costs, environmental pollution, and a lack of product traceability (Aung et al., 2025). n response to these challenges, artificial intelligence (AI) and the Internet of Things (IoT), collectively known as the Artificial Intelligence of Things (AIoT), are driving significant advancements in the aquaculture industry, offering solutions to longstanding challenges related to operational efficiency, sustainability, and productivity (Huang and Khabusi, 2025). IoT sensors deployed across aquaculture systems continuously track critical parameters such as temperature, pH, dissolved oxygen, salinity, and fish behavior, while AI algorithms process these data streams to provide predictive insights into water quality management, disease detection, species identification, biomass estimation, and optimized feeding strategies (Huang and Khabusi, 2025). Furthermore, the integration of smart biofloc systems using AI and IoT technologies enables automated processes, optimized resource utilization, and improved overall system performance (Haraz, 2025). AI-driven tools such as computer vision, machine learning, and predictive modelling hold much potential for enhancing sustainability, efficiency, and productivity within aquaculture operations through applications such as disease monitoring, environmental management, and production optimization (Aung et al., 2025). This article reviews the major technological domains through which AI is reshaping aquaculture, examining intelligent water quality monitoring, smart feeding systems, disease detection, biomass estimation, risk management, and future directions in the field.

The AI & IoT Revolution in Aquaculture: Foundations and Scope

Since the 1950s, aquaculture's share of global fisheries output has risen from 4% to nearly half of total fish production in 2020, with an estimated market value of USD 265 billion as of 2020 (Huang and Khabusi, 2025). The growing complexity of aquaculture operations has necessitated the adoption of digital technologies, and the convergence of AI and IoT, referred to as AIoT, represents a transformative shift in this regard (Tina et al., 2025). AIoT applications in aquaculture span a broad spectrum of innovations, including smart feeding systems, water quality management, disease detection, fish biomass estimation, fish behavior monitoring, organism counting, species segmentation and classification, breeding and growth estimation, individual fish tracking, and automation and robotics (Huang and Khabusi, 2025). The increasing global demand for seafood underscores the necessity for sustainable aquaculture practices, yet several challenges, including rising operational costs, variable environmental conditions, and the threat of disease outbreaks, impede progress in this field (Tina et al., 2025). By integrating technologies such as the IoT and cloud computing, intelligent data processing, analysis, optimization, and decision-making can be effectively implemented within smart aquaculture systems (Aung et al., 2025). Emerging technologies such as edge computing, blockchain, and hybrid AI models hold further promise for enhancing AIoT's role in aquaculture, where edge computing enables faster, decentralized data processing while blockchain improves data security and traceability (Huang and Khabusi, 2025). The principal goal of precision fish farming is to use data and new technologies such as sensors, cameras, and internet connections to optimize fish-aquaculture operations, making them data-driven, accurate, and repeatable, thereby reducing the effects of subjective choices by farmers (Tina et al., 2025).

AI-Powered Water Quality Monitoring and Environmental Control

Maintaining optimal physicochemical parameters, such as pH, temperature, and dissolved oxygen, is critical in aquatic production systems, as imbalances in these variables can negatively affect both nutrient availability and fish welfare (Fandiño Pelayo et al., 2025). Studies have shown that fluctuations in pH can alter the solubility and bioavailability of nutrients, compromising plant uptake and increasing physiological stress in fish, while inadequate dissolved oxygen levels are associated with reduced fish growth, immunosuppression, and higher mortality rates (Fandiño Pelayo et al., 2025). Temperature also plays a crucial role, affecting metabolic activity, microbial dynamics, and the efficiency of nitrification processes, and therefore controlling these key variables ensures not only nutrient stability but also the overall resilience of aquaponic systems (Fandiño Pelayo et al., 2025). In addressing these monitoring needs, Fandiño Pelayo et al. (2025) developed a predictive system based on AI and environmental sensing for aquaponic systems, integrating low-cost digital sensors to continuously measure key physicochemical variables, including pH, dissolved oxygen, and temperature, and using these as inputs for real-time classification of fish health status. Four supervised machine learning models were evaluated, namely linear discriminant analysis (LDA), support vector machines (SVMs), neural networks (NNs), and random forest (RF), using a dataset of 1,823 instances collected over eight months from a red tilapia aquaponic setup (Fandiño Pelayo et al., 2025). The random forest model yielded the highest classification accuracy at 99%, followed by NN at 98% and SVM at 97%, with LDA achieving 82% accuracy (Fandiño Pelayo et al., 2025). Water quality management systems in broader AIoT frameworks similarly utilize IoT sensors and predictive models such as Long Short-Term Memory (LSTM) networks and Kalman filtering to monitor critical parameters such as dissolved oxygen, pH, and temperature, allowing for real-time intervention and ensuring optimal aquatic conditions (Huang and Khabusi, 2025). Biofloc technology (BFT), which leverages microbial communities to enhance water quality, reduce feed costs, and improve fish health, is also being integrated with AI and IoT to automate processes, optimize resource utilization, and boost overall system performance (Haraz, 2025). IoT devices in smart BFT systems facilitate real-time monitoring, while AI-driven analytics provide actionable insights for predictive management, enabling a comparative analysis of AI models such as LSTM, Random Forest, and Support Vector Machine for various aquaculture prediction tasks, with performance measured through metrics like root mean squared error (RMSE) and mean absolute error (MAE) (Haraz, 2025).

Smart Feeding Systems and Biomass Estimation

Feeding represents one of the largest operational costs in aquaculture, and its optimization is therefore both an economic and environmental priority (Aung et al., 2025). Smart feeding systems represent a key application area where AI models such as ResNet and gradient boosting machines analyze fish behavior and feeding patterns to automate feeding schedules, improving feed conversion ratios and growth rates while minimizing wastage (Huang and Khabusi, 2025). However, the performance of such systems is often influenced by species-specific behavior and environmental conditions, highlighting the need for adaptive, context-sensitive approaches (Huang and Khabusi, 2025). Computer vision technologies are central to modern biomass estimation, which is fundamental to precision aquaculture and directly influences feeding strategies, harvesting schedules, and economic forecasting (Tina et al., 2025). Traditionally, biomass estimation was conducted by sampling with an error often exceeding 10 to 15%, yet AI-powered fully automatic biomass estimation systems for free-moving fish using deep learning models have achieved estimation errors of less than 5% on average in tests compared to actual measurements (Theodorou, 2026). Convolutional neural network-based models such as ResNet and VGG further facilitate species identification and population monitoring, ensuring compliance with regulations and maintaining biodiversity (Huang and Khabusi, 2025). The integration of computer vision, machine learning, and sensor technologies into recirculating aquaculture systems additionally allows producers to better manage system conditions and respond proactively to changes in fish health and growth (Aung et al., 2025).

AI-Driven Disease Detection and Risk Management

Disease outbreaks represent one of the most significant threats to aquaculture productivity, with economic losses caused by viral, bacterial, and fungal diseases in the aquaculture industry estimated at six billion USD annually (Aung et al., 2025). In some aquaculture operations, camera systems and AI are already being used to monitor animal behavior and facilitate the early diagnosis of marine parasites or diseases, yet the lack of sufficient real-time data from units, the cost of implementing sensors, and the need for managers to trust automated recommendations are often cited as challenges (Theodorou, 2026). In the context of disease detection, AI models and deep learning techniques have been effectively applied to synthesize realistic visual data representing diseases such as sea lice infestations, fungal infections, and bacterial diseases, and by training automated diagnostic models on enriched datasets, the accuracy and reliability of automated visual diagnostic systems have been notably improved (Tina et al., 2025). AI-driven models additionally facilitate continuous health assessments by accurately predicting disease progression, enabling proactive interventions and significantly improving animal welfare and farm productivity (Tina et al., 2025). A systematic PRISMA review of machine learning applications in aquaculture risk management identified that while AI and ML tools offer new predictive capabilities for risk quantification, there is a significant disconnection between algorithmic predictions and operational action, with only 3 of 38 reviewed studies demonstrating integration with standardized risk management frameworks such as ISO 31000 (Theodorou, 2026). Haraz (2025) emphasized that AI model reliability, interpretability through explainability tools such as SHAP and LIME, uncertainty quantification, and failure mode analysis must all be addressed, advocating for robust testing protocols and human-in-the-loop systems to ensure that predictive outputs translate into effective management actions. The study concluded that while AI tools provide predictive efficiency, interdisciplinary frameworks are required to filter predictions through economic and ethical criteria, and that strengthening this connection will bring the use of AI closer to proactive and standardized risk mitigation (Haraz, 2025).

Challenges and Future Directions for Smart Aquaculture

Despite the remarkable progress in AI-driven aquaculture, significant challenges remain before these technologies can be universally adopted. High implementation costs, data privacy concerns, and the need for robust, generalizable models that perform reliably across diverse species and environmental conditions represent persistent barriers (Huang and Khabusi, 2025). Most existing studies focus on optimizing individual physicochemical parameters without directly linking these factors to biological indicators in fish, limiting the ability of aquaponic systems to proactively respond to critical events that compromise system productivity and sustainability (Fandiño Pelayo et al., 2025). Research gaps remain in the integration of AI in broodstock management, the development of multimodal AI systems, and the challenge of model generalization across contexts (Tina et al., 2025). Challenges related to sensor biofouling and the need for recalibration in diverse aquatic environments remain prominent concerns for water quality management systems (Huang and Khabusi, 2025). Furthermore, a structured review of AI methods in aquaculture identified that while disease detection and feeding behavior identification are the most researched areas, there is comparatively less work on supply chain traceability, multi-species systems, and the integration of AI outputs into formal regulatory frameworks (Aung et al., 2025). Looking ahead, future directions include the development of hybrid AI models, improved scalability for large-scale operations, and sustainable resource management frameworks that can combine the benefits of IoT sensing with the predictive power of machine learning (Huang and Khabusi, 2025). The environmental and economic impacts of AI-integrated biofloc systems, including quantitative case studies on cost reduction and productivity increases, underscore the transformative potential of these technologies in advancing sustainable aquaculture practices, offering a pathway to more resilient and efficient food production (Haraz, 2025).

Conclusion

The integration of artificial intelligence and IoT technologies into aquaculture operations marks a decisive shift from reactive, labor-intensive fish farming toward intelligent, data-driven production systems. From real-time water quality monitoring and precision feeding to early disease detection and biomass estimation, AI-enabled tools are demonstrably improving efficiency, sustainability, and fish welfare. However, the evidence also reveals critical gaps: algorithmic predictions are rarely linked to standardized operational frameworks, implementation costs remain high, and model generalizability across species and environments requires further research. Bridging these gaps through interdisciplinary collaboration among engineers, biologists, policy makers, and farmers will be essential to fully realizing the promise of smart fish farms as a cornerstone of the global sustainable food system.

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