Artificial Intelligence of Things: Driving Next-Generation Aquaculture Practices

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Abstract

Artificial Intelligence of Things (AIoT) is transforming aquaculture by integrating IoT-enabled sensing with AI-driven analytics to improve sustainability, efficiency fish welfare. Sensors monitor water quality, fish behavior, biomass stock counts, while communication protocols ensure reliable data transfer. Machine learning and deep learning enable prediction, disease detection adaptive management robotics with digital twins automate monitoring and resource use. Together, these technologies create a resilient, scalable framework for modern aquaculture.

Keywords: Aquaculture, AIoT, IoT sensors, machine learning, deep learning, water quality, disease detection, biomass estimation, robotics, sustainability

1. Introduction

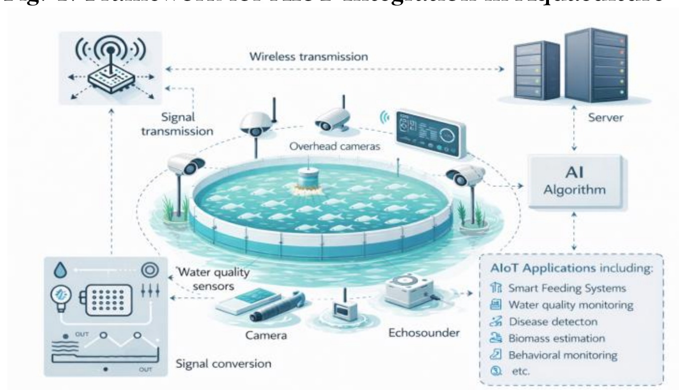
Aquaculture is the controlled farming of aquatic organisms such as fish, shrimp, mollusks, seaweeds more meeting rising seafood demand while easing pressure on wild stocks. Recent advances in AIoT (Artificial Intelligence + Internet of Things) are transforming the field: sensors and cameras collect continuous data on water quality, feeding fish behavior, while AI analyzes these streams for real-time decisions, predictive analytics automation. Applications include smart feeding, disease detection, biomass estimation, species classification, breeding optimization robotics. Autonomous underwater vehicles now perform inspections and feeding with minimal human input.

Aquaculture has grown rapidly, now producing nearly half of global fish output and projected to surpass capture fisheries by 2030. While disease, environmental variability feeding inefficiencies remain challenges, AIoT with edge computing, blockchain hybrid AI models offers scalable, secure sustainable solutions, positioning aquaculture as a cornerstone of future food security and environmental resilience.

2. Components of AIoT in Aquaculture

AIoT in aquaculture combines two key elements: IoT sensors that capture real-time data on water quality and fish behavior AI algorithms that process this information to guide decisions. Supported by communication technologies like LoRa, NB-IoT 5G, these systems ensure reliable data transfer from farms to management platforms. Together, they enable automated, data-driven practices that boost efficiency, minimize waste promote sustainable aquaculture.

Fig. 1. Framework for AIoT Integration in Aquaculture



2.1 Sensors of IoT

IoT sensors make aquaculture smarter by enabling continuous monitoring of key parameters like oxygen, temperature water quality. They provide early alerts for harmful changes, helping farmers act quickly with aeration or adjustments. Beyond this, IoT systems support early disease detection, optimize feeding reduce pollution, making fish farming more resilient, efficient sustainable.

2.1.1 Water Quality Sensors

Water quality sensors are central to aquaculture, continuously monitoring pH, temperature, dissolved oxygen, salinity ammonia factors vital for fish health and growth. Even small changes can trigger stress or disease. Innovations have improved sensor accuracy, durability affordability: ISFET sensors resist harsh conditions better than glass electrodes for pH, optical sensors outperform electrochemical ones for oxygen inductive salinity sensors reduce fouling. Ammonia is tracked with ion-selective electrodes or slower colorimetric methods. Despite challenges like drift and maintenance, research is advancing anti-biofouling materials and integrated multi-sensor systems for more reliable, real-time monitoring.

2.1.2 Optical Sensors

Optical sensors are key tools in aquaculture, monitoring water clarity and turbidity to detect risks like pollution or algal blooms. Turbidity sensors measure light scattering or absorption, while camera-based computer vision tracks fish behavior to spot stress or disease early and optimize feeding. Though biofouling can reduce accuracy, optical sensors remain practical and cost-effective for proactive water quality management and sustainable farming.

2.1.3 Motion Sensors

Motion sensors, especially accelerometers, are powerful tools in aquaculture for non-invasive monitoring of fish activity, feeding stress. Embedded in tags or attached externally, they capture movement data like tail-beat frequency or rest periods, revealing subtle changes linked to water quality or illness. Combined with telemetry, they enable real-time, remote tracking, helping farmers quickly respond to shifts in health and productivity.

2.2 Deployment Strategies

IoT sensor deployment in aquaculture hinges on choosing the right protocol and placement. LoRa suits large, remote farms with long-range, low-power use, 5G enables real-time video with high speed and low latency NB-IoT balances efficiency and range for water quality sensors. Strategic distribution across depths and locations ensures accurate monitoring of temperature, oxygen other parameters.

2.3 AI Algorithms

AI algorithms transform aquaculture by turning sensor data into actionable insights. They drive predictive modeling, automation optimization of feeding and water management, while methods like machine learning, deep learning, computer vision fuzzy logic enable efficient analysis of complex datasets to tackle key challenges.

2.4 Machine Learning (ML)

Machine learning enhances aquaculture by turning IoT sensor data into predictions and adaptive decisions. Supervised methods classify water quality and detect disease, regression models forecast growth or temperature unsupervised clustering reveals patterns or anomalies. Reinforcement learning optimizes feeding, aeration resource use, with advanced approaches enabling complex, real-time management. Overall, ML improves efficiency, sustainability fish health.

2.5 Deep Learning (DL)

Deep learning applies multi-layer neural networks to complex aquaculture data, enabling accurate prediction and monitoring. Feedforward networks handle structured data, while CNNs (like VGG or ResNet) excel in image-based tasks such as species identification and health checks. U-Net and YOLO support segmentation and real-time detection for population and behavior analysis. RNNs and LSTMs process sequential data to forecast oxygen levels or feeding patterns. Autoencoders detect anomalies in sensor streams MLPs classify water quality. Together, these architectures make deep learning indispensable for efficient, sustainable aquaculture management.

2.6 Computer Vision and Image Processing

Computer vision and image processing are vital in aquaculture, enabling AI to interpret video data for monitoring fish health and behavior. Techniques such as edge detection, segmentation object tracking allow for biomass estimation, movement analysis early detection of stress or disease. By analyzing swimming patterns and abnormal behaviors, these tools provide actionable insights that support responsive management strategies and sustainable farming practices.

2.7 Fuzzy Logic Control

Fuzzy logic, which mimics human reasoning to handle uncertainty, is highly effective in aquaculture. It has been applied to disease diagnosis, feeding optimization behavioral monitoring by combining expert knowledge, image analysis sensor data. These systems improve efficiency, reduce waste support sustainable fish farming.

2.8 AIoT Pipeline

Fig. 2 AIoT system pipeline for aquaculture

This pipeline starts with IoT sensors, cameras aerial systems collecting real-time data on water quality, feeding fish behaviour. Data are sent wirelessly to servers, then preprocessed for consistency. AI algorithms analyze the inputs to generate insights for smart feeding, water quality prediction, disease detection, biomass estimation species classification. Together, these steps enable efficient, automated sustainable aquaculture management.

3 AIoT Applications in Aquaculture

3.1 Smart Feeding Systems

Smart feeding systems automate aquaculture feeding by monitoring fish activity and environmental conditions to deliver food efficiently at the right time. Approaches include optimizing feeding schedules and nutrient balance, detecting feeding behavior with computer vision, assessing feeding intensity through acoustic monitoring, applying AI-driven precision systems for dynamic adjustments integrating multimodal data for a holistic view of feeding. Collectively, these methods reduce waste, improve growth support sustainable aquaculture practices.

Fig. 3 Practical applications of AIoT in aquaculture

3.2 Water Quality Management

Water quality management in aquaculture integrates continuous monitoring, predictive modeling proactive intervention to keep environments stable and healthy. IoT sensors track parameters like temperature, pH, salinity, oxygen, turbidity, chlorophyll ammonia in real time. AI analytics forecast changes, detect anomalies anticipate risks such as oxygen depletion or algal blooms. Automated systems then adjust aeration, feeding, filtration, or treatments to stabilize conditions. This approach safeguards fish health, boosts growth, reduces waste supports long-term sustainability, making aquaculture more resilient and efficient.

3.3 Disease Detection and Classification

Early disease detection is vital in aquaculture to protect stock health, reduce mortality avoid losses. Modern systems combine computer vision, water-quality-based prediction AI techniques for fast, accurate diagnosis. Vision models spot visible symptoms, predictive models anticipate risks from environmental data advanced methods like cross-modal or zero-shot learning extend detection to diseases with limited datasets. Ensemble and hybrid models improve robustness, while neuro-fuzzy systems enhance precision. Mobile and IoT platforms make monitoring scalable biosensors provide direct pathogen detection. Together, these tools create a comprehensive framework for proactive disease management and sustainable aquaculture.

3.4 Fish Biomass Estimation

Fish biomass estimation is essential for aquaculture, guiding health, growth population management while reducing waste. Modern methods replace manual checks with non-invasive, real-time tools powered by AI and sensors. Computer vision and deep learning analyze underwater images, sonar and acoustic systems work well in turbid or dense environments 3D modeling reconstructs fish volumes for precise measurements. Smart scales and acoustic signal processing add portable and species-specific options. Together, these technologies enable efficient feeding, better resource use sustainable practices.

3.5 Fish Behavior Detection

Monitoring fish behavior is crucial in aquaculture, as changes often signal stress, disease, feeding status, or environmental imbalance. AI, IoT, computer vision acoustic tools enable non-invasive, real-time observation. Systems detect abnormal swimming or lethargy, track speed and locomotion link behavior to disease risks. Shoaling analysis reveals group dynamics, while acoustic monitoring extends detection in turbid waters. Together, these methods provide continuous welfare assessment, supporting healthier stocks, optimized growth sustainable practices.

3.6 Counting Aquaculture Organisms

Accurate organism counting is vital in aquaculture for stock assessment, feeding health monitoring. Manual methods are labor-intensive, but AI, computer vision sensors now enable automated, non-invasive counting across fish, shrimp holothurians. Deep learning supports shrimp larvae and seed counting, while CNNs, YOLO density networks handle fish in crowded environments. Acoustic and echosounder systems work well in turbid waters 3D or non-contact frameworks extend detection to other species. These innovations provide precise, scalable sustainable monitoring.

3.7 Segmentation, Detection Classification of Aquaculture Species

Segmentation, detection classification of aquaculture species are essential for effective monitoring, stock management biodiversity conservation. Advances in AI and computer vision have enabled robust solutions that work even in challenging underwater and satellite imaging conditions.

- **Fish Species Classification**: Deep learning and AIoT systems identify species with high accuracy, supporting ecological monitoring and fisheries management. Models range from CNNs and vision transformers to ensemble approaches, enabling recognition across diverse datasets and environments.
- **Underwater Species Detection**: Enhanced YOLO and R-CNN variants improve detection in low-quality, blurred, or occluded underwater images, supporting real-time monitoring in complex environments.
- **Segmentation in Underwater and SAR Images**: Transformer-based and U-Net models provide precise segmentation of aquaculture zones, rafts marine

structures, ensuring accurate resource mapping and large-scale monitoring.

- **Aquaculture Structure Detection**: Specialized clustering and segmentation algorithms identify floating rafts and other structures in SAR imagery, aiding environmental management and operational planning.
- **Fish Quality Assessment**: Image processing techniques segment gills, scales other features to evaluate freshness and quality, supporting automated seafood validation in farming and retail contexts.

Together, these approaches form a comprehensive framework for aquaculture monitoring, combining ecological insights with practical applications in stock management, structural detection product quality assessment.

3.8 Breeding and Growth Estimation

Breeding and growth estimation in aquaculture focus on optimizing feeding, health, reproduction sustainability. Automated breeding and spawning detection systems improve reproductive success, while echosounders and digital twins provide accurate population estimates for better stock management. Growth estimation techniques using stereo vision, CNNs YOLO-based models enable precise, non-invasive measurement of fish size and weight, supporting efficient feeding and monitoring. Environmental monitoring complements these systems by detecting external risks such as algal or jellyfish blooms. Together, these technologies create an integrated framework for managing breeding, growth environmental safety in aquaculture.

3.9 Fish Tracking and Individuality

Fish tracking is vital for monitoring health, feeding, breeding population dynamics in aquaculture. AIoT technologies now enable accurate, non-invasive tracking at both individual and group levels. Biometric methods like iris recognition support individual identification, while multi-fish tracking systems handle crowded environments using video, motion analysis detection frameworks. Sonar and echogram-based approaches extend monitoring to turbid waters, improving activity segmentation. Group behavior recognition models capture shoaling and collective dynamics specialized algorithms track fish around marine structures or with moving cameras. Together, these methods provide a comprehensive framework for behavior and population monitoring, enhancing aquaculture efficiency and sustainability.

3.10 Automation and robotics in aquaculture

Automation and robotics are reshaping aquaculture by boosting sustainability, resource efficiency monitoring. Remote sensing integrates IoT, big data satellite imagery to track water quality and farm zones. Robotic systems such as ROVs, UAVs AUVs support inspections, feeding automation resilience against harsh conditions. Hybrid setups combine IoT, robotics imaging for tasks like shrimp counting or defect detection. Advanced imaging and sensors improve species detection and forecasting, while digital twins optimize feeding and mortality prediction. Biologically inspired robots enhance mobility and adaptive monitoring renewable-powered systems strengthen resilience. Collectively, these innovations create a technology-driven framework for sustainable aquaculture.

4 Advantages of AIoT in Aquaculture

AIoT revolutionizes aquaculture by automating monitoring, feeding disease detection with greater accuracy and efficiency than traditional manual methods. IoT sensors enable continuous environmental tracking, predictive analytics forecast risks like oxygen depletion AI-driven video analysis optimizes feeding schedules to reduce waste. Digital twins allow remote management and simulation of aquaculture systems, while renewable-powered IoT devices cut costs and emissions. Together, these innovations enhance productivity, sustainability resilience in fish farming.

5 Challenges and Limitations of AIoT in Aquaculture

AIoT adoption in aquaculture faces several challenges despite its transformative potential. High initial costs and infrastructure requirements make it difficult for small and medium farms to invest in sensor networks, data systems computational resources. Environmental variability such as fluctuations in water quality, temperature salinity limits model adaptability and often requires costly retraining. Data privacy and security concerns arise from continuous IoT data collection, demanding strong encryption and secure architectures. Scalability is another hurdle, as deploying thousands of sensors and managing large datasets is often beyond the reach of smaller operators. Technical expertise requirements add complexity, since aquaculture farmers may lack the skills to implement and maintain AIoT systems. Furthermore, most AI models are species- or environment-specific, reducing generalizability across diverse aquaculture operations. Finally, energy-intensive data processing and device deployment raise ecological concerns, potentially undermining sustainability goals.

6 Future Directions of AIoT in Aquaculture

AIoT in aquaculture still faces key challenges future work should focus on making systems more adaptive, scalable sustainable. Real-time adaptability will help farms respond instantly to environmental changes. Species-specific and environmental adaptability requires multimodal data and transfer learning for broader generalization. Cost-effective, scalable solutions like mobile sensors and cloud platforms will make AIoT accessible to smaller farms. Integrated multimodal monitoring can provide a holistic view of fish welfare, while real-time biosensing will strengthen disease detection. Robotics must evolve toward autonomous, energy-efficient systems, supported by renewable energy solutions for remote farms. Finally, digital twins and predictive analytics will enable proactive management, simulating scenarios to optimize feeding, reduce risks improve decision-making.

7 Conclusion

AIoT is transforming aquaculture by tackling inefficiencies, disease management sustainability challenges across ten key areas: smart feeding, water quality, disease detection, biomass estimation, behavior monitoring, organism counting, species classification, breeding and growth estimation, fish tracking automation. Each area shows strong progress like adaptive feeding systems, predictive water quality monitoring, biosensors for disease robotics for offshore operations but also faces hurdles such as high costs, limited generalization across species data privacy concerns.

Future work should focus on real-time adaptability, multimodal monitoring, cost-effective scalability sustainable energy integration. Digital twins and predictive analytics will enable proactive management, while robotics and biosensing will enhance efficiency and resilience. Overall, AIoT offers transformative potential, but bridging gaps in affordability, technical expertise environmental adaptability will be key to widespread adoption.

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