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The artificial intelligence of things and its aquaculture applications

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Study categorizes AIoT applications into 10 core areas, each highlighting unique methodologies, key achievements and potential for future advancements

The integration of artificial intelligence (AI) and the internet of things (IoT), known as artificial intelligence of things (AIoT), is driving significant advancements in the aquaculture industry, offering solutions to longstanding challenges related to operational efficiency, sustainability, and productivity. This review explores the latest research studies in AIoT within the aquaculture industry, focusing on real-time environmental monitoring, data-driven decision-making, and automation. Photo of auto-feeders at a shrimp pond by Fernando Huerta.

Aquaculture continues to evolve as a vital component of modern agriculture and environmental management through the facilitation of artificial intelligence of things (AIoT), which integrates artificial intelligence (AI) and internet of things (IoT) to enhance fish farming practices. For instance, digital twins enable **real-time monitoring and decision-making** (https://doi.org/10.1016/j.atech.2023.100285), sustainable IoT solutions reduce **resource wastage and promote environmental resilience** (http://dx.doi.org/10.1109/JSEN.2022.3188639), IoT-based systems improve **disease detection and health management** (https://doi.org/10.23919/mipro52101.2021.9597005), and AIoT-driven water quality inspection systems **enhance operational efficiency and scalability** (http://dx.doi.org/10.1109/JSEN.2023.3340295).

The development of IoT devices, including sensors, cameras, and monitoring systems, has revolutionized data collection from remote and dynamic aquaculture environments. These devices provide continuous streams of data on critical parameters – such as water quality, fish behavior, feeding patterns, and environmental conditions – and AI algorithms analyze these data to generate actionable insights that drive real-time decision-making and autonomous operations, thereby reducing human intervention and **enabling smarter, more sustainable practices** (http://dx.doi.org/10.1109/JSEN.2022.3151777).

The **foundational IoT infrastructure in aquaculture** (https://doi.org/10.1016/j.atech.2023.100187) consists of data-gathering devices, connectivity gateways, and cloud platforms for data storage and processing. This infrastructure supports real-time monitoring and analysis of environmental parameters like temperature, salinity, pH, and dissolved oxygen; factors critical for maintaining optimal aquatic conditions. Cloud computing enables the parallel processing and scalability needed to handle large-scale datasets efficiently, providing a **robust platform for integrating AI capabilities** (https://doi.org/10.1007/s10499-024-01701-2) into aquaculture systems.

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. For instance, IoT-enabled smart feeding systems utilize data from sensors and underwater cameras to monitor fish behavior and optimize feeding schedules and quantities. The AI models applied in this study analyze the collected data to ensure fish are fed adequately while minimizing waste, improving growth rates, and reducing environmental impact.

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This article – **summarized** (https://creativecommons.org/licenses/by/4.0/) from the **original publication** (https://doi.org/10.3390/pr13010073)– discusses a review which comprehensively analyzed advancements in AIoT applications within aquaculture, drawing from 215 research papers published between 2012 and 2024. The papers are systematically categorized into ten core application areas: 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.

The review also explores AIoT advantages, adoption challenges such as high implementation costs, data privacy concerns, and the need for scalable and adaptable AI models across diverse environments. It also highlights future AIoT trends, including the development of hybrid models, scalability solutions, and AIoT's role in promoting sustainable aquaculture practices. By providing an in-depth analysis of the long-term potential of AIoT, this review paper highlights its transformative role in advancing global aquaculture practices and sustainability.

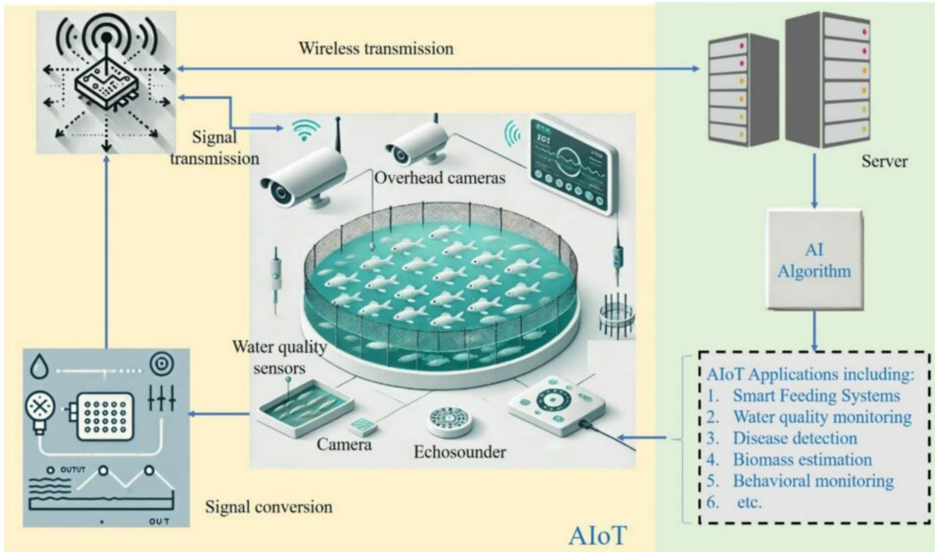

Fig 1: Conceptual framework of AIoT in aquaculture.

AIoT applications in aquaculture

Integrating AIoT into aquaculture is revolutionizing farm management by merging real-time IoT sensor data collection with advanced AI-driven analytics. This synergy is enhancing efficiency, sustainability, and productivity in aquaculture operations.

Smart feeding systems

Smart feeding systems represent a transformative application area in aquaculture. These applications monitor fish feeding activity and environmental parameters to automate feeding, ensuring aquatic organisms receive the appropriate amount of food at optimal times. Research to date has provided a solid foundation for smart feeding systems, exploring various methods to enhance feeding strategies and efficiency. These methods include optimization of feeding frequency and nutrient distribution using various models to refine feeding schedules and improve growth rates, automated detection of feeding behavior using advanced computer vision techniques, and real-time feed detection systems, acoustic-based monitoring to correlate feeding sound intensity with hunger levels and classify feeding intensity using models,

AI-enhanced precision feeding systems for real-time feeding adjustments, and integration of multimodal data to provide a comprehensive understanding of feeding behavior.

Water quality management

Maintaining optimal water quality is fundamental for sustainable and productive aquaculture, as aquatic species’ health, growth, and welfare are directly influenced by environmental conditions. Deviations in parameters like dissolved oxygen, pH, temperature, and ammonia levels can significantly affect fish health, impacting growth rates and disease susceptibility. Integrating IoT sensors and AI-based predictive analytics has proven essential in modern aquaculture, enabling continuous, real-time monitoring and early intervention to prevent adverse conditions.

Studies have demonstrated that proactive monitoring systems can effectively forecast critical events in aquaculture. For instance, for predicting critical aquaculture events such as oxygen depletion and water quality deterioration; the ability to predict algal blooms and maintain environmental stability through AI-driven monitoring; the use of genetic algorithms combined with ensemble learning to optimize dissolved oxygen predictions; and model for accurate marine temperature prediction, which indirectly supports forecasting algal blooms and related events.

Disease detection and classification

Early disease detection and classification are vital for effective control and management of disease outbreaks in aquaculture farms. This ultimately contributes to the health and productivity of fish and shrimp stocks. Disease outbreaks not only affect the welfare of cultured species but also lead to significant economic losses in fish farming practices. Advancements in biosensor technology contribute to disease prevention by providing precise pathogen detection capabilities. Relevant areas include computer vision-based disease detection, water quality-linked disease prediction, cross-modal and zero-shot learning for disease identification, ensemble and hybrid models for disease classification, adaptive neural fuzzy systems, mobile and IOT-enabled disease monitoring systems, and biosensors for pathogen detection.

Fish biomass estimation

Fish biomass estimation is critical in optimizing aquaculture operations by enabling accurate assessments of fish health, growth, and population density. Reliable biomass estimation facilitates efficient feeding routines, reduces waste accumulation, and promotes sustainable fish farming practices. Modern advancements in machine learning, computer vision, sonar, and smart scale technologies have enabled non-invasive, real-time biomass estimation in aquaculture, overcoming traditional challenges associated with manual measurements and stress-induced inaccuracies.

Fish behavior detection

Monitoring fish behavior is critical for maintaining fish health, welfare, and achieving optimal growth in aquaculture systems. Behavioral changes often serve as early indicators of stress, disease, satiety or hunger, and adverse environmental conditions, providing valuable insights for timely interventions. Recent advancements in AI, IoT, acoustic monitoring, and computer vision have revolutionized behavior detection, enabling non-invasive, real-time monitoring even in complex aquaculture environments. These technologies have demonstrated significant improvements in accuracy and reliability, as evidenced by various studies.

Counting aquaculture organisms

Accurate counting of organisms in aquaculture is vital for managing stock, monitoring health, and optimizing feeding. Traditionally, this task has been labor-intensive, invasive, and prone to inaccuracies, especially in high-density environments. Recent developments in AI, computer vision, and sensor technologies have made automated, accurate counting feasible for a variety of aquaculture species, including fish, shrimp and holothurians. Existing studies have reported considerable success in counting aquaculture organisms using smartphone-based deep learning models for counting shrimp; or applying computer vision for behavioral study and fish counting in controlled environments; using an echosounder-based algorithm for estimating fish populations in farming nets.

Segmentation, detection and classification of aquaculture species

The segmentation, detection, and classification of aquaculture species are critical tasks for effective aquaculture monitoring and biodiversity conservation. Advances in AI and computer vision have introduced robust solutions for these tasks, even in challenging underwater conditions. This area involves the recent research studies that address the complexity of recognizing aquaculture species and marine structures in a variety of environments.

Breeding and growth estimation

Breeding and growth estimation in aquaculture is essential for optimizing fish feeding, fish health evaluation, reproductive success, and environmental safety. Recent studies have focused on developing automated and accurate techniques to estimate growth parameters and monitor breeding maturity, utilizing advanced AI models, computer vision, and stereo vision technology. This area includes applications like automated breeding and spawning detection, fish population estimation using echosounders and digital twins, growth estimation, and environmental monitoring for growth and health.

Fish tracking and individuality

Critical for monitoring fish behavior, health, feeding patterns, breeding, and population dynamics in both controlled and natural environments. Recent advancements in AIoT have enabled more accurate and scalable solutions for individual and group tracking and behavior analysis in complex aquatic environments. Areas of interest include individual fish identification, multi-fish tracking in controlled and unconstrained environments, activity segmentation and tracking in sonar and echogram data, fish group activity and behavior recognition, tracking fish around marine structures and moving cameras, and individuality and behavior tracking for aquaculture monitoring.

Automation and robotics in aquaculture

Automation and robotics in aquaculture employ autonomous underwater vehicles (AUVs) and reinforcement learning algorithms to automate tasks such as tank cleaning, fish inspection, and feed delivery. While robotics improves operational efficiency, limitations like battery life, connectivity, and implementation costs hinder scalability. These diverse applications address a wide range of challenges for sustainable fish farming, resource management, and environmental conservation, and include remote sensing and monitoring systems, robotic and autonomous systems for underwater monitoring, UAV- and AUV-based aquaculture inspections, hybrid and smart monitoring systems, advanced imaging and sensor, technologies, digital twin and predictive modeling, biologically inspired robotics, and specialized aquaculture applications which expand the scope of robotics in aquaculture.

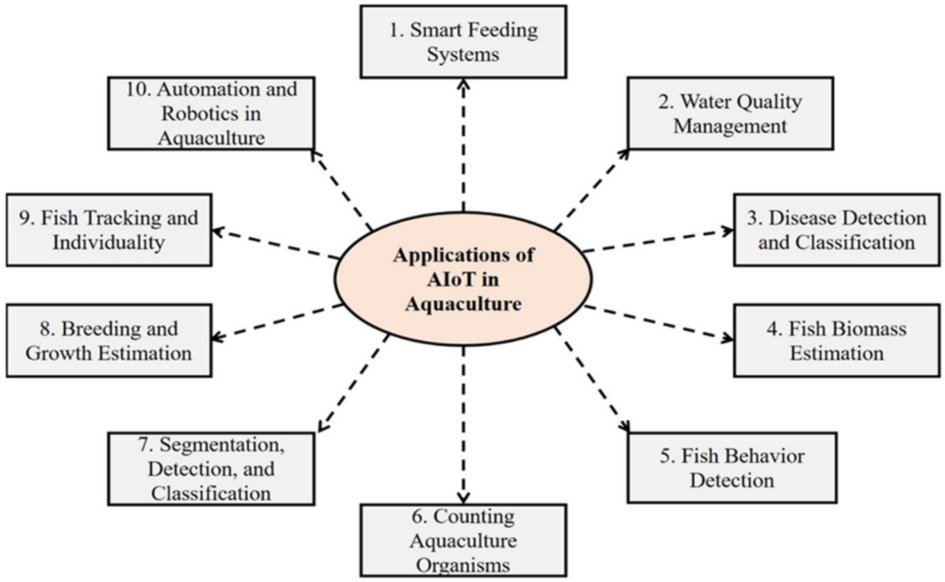

Fig 2: Applications of AIoT in aquaculture.

Concluding remarks and future work

Integrating AI and IoT contributes to the advancement of aquaculture by effectively addressing critical challenges such as operational inefficiencies, environmental sustainability, disease management, and resource optimization. This review categorizes AIoT applications into ten core areas: smart feeding systems, water quality management, disease detection, fish biomass estimation, fish behavior detection, counting aquaculture organisms, species segmentation and classification, breeding and growth estimation, fish tracking and individuality, and automation and robotics. Each area highlights unique methodologies, key achievements, and potential for future advancements.

Among these, smart feeding systems exemplify how AIoT optimizes feeding schedules, minimizes waste, and enhances feed efficiency, significantly improving growth rates. Future research in this area is expected to develop adaptive systems and leverage cloud-based monitoring to ensure scalability and robustness. Similarly, water quality management has progressed with real-time monitoring and predictive adjustments enabled by AIoT, helping to maintain optimal conditions for fish welfare. However, challenges such as scaling across diverse environments and incorporating edge computing solutions for real-time processing remain priorities for future development.

In disease detection and prevention, AI-driven biosensors and IoT tools enable early detection of health issues, reducing mortality rates and improving overall fish health. Nonetheless, the lack of robust datasets and generalized models limits cross-species applicability, requiring further research. Fish biomass estimation, a critical component for yield forecasting, has been improved through computer vision and acoustic analysis techniques. Advancing this area will require refining multimodal systems for varied environments and enhancing real-time capabilities. AIoT also plays a vital role in the detection of fish behavior, where models analyze patterns indicative of stress, disease, or social dynamics.

Eight digital technologies disrupting aquaculture

Eight digital technologies are disrupting aquaculture and having a profound impact on the way business operates – even displacing some established ones.

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Despite notable progress, challenges such as environmental variability, noise interference, and species-specific behaviors necessitate the development of more adaptable and species-diverse models. Similarly, automated counting methods for aquaculture organisms streamline management but face issues such as occlusion and environmental variability. These methods need further refinement to ensure broad applicability and versatility.

Species segmentation and classification showcase the potential of advanced AI techniques in distinguishing species under complex conditions. Yet, ensuring adaptability to diverse environments and integrating low-power, real-time deployment solutions remains a challenge. In the context of breeding and growth estimation, models assessing fish maturity and growth rates are advancing breeding efficiency. Expanding these models to accommodate various species and integrating continuous real-time data are critical steps for more robust monitoring systems.

Fish tracking and individuality monitoring provide valuable insights into behavior and the effects of water quality, but challenges persist in high-density and diverse aquaculture environments. Integrating multiple data sources could improve comprehensiveness and precision. Finally, automation and robotics are revolutionizing labor-intensive tasks, especially in offshore or remote locations, by enabling real-time monitoring and execution. Future advancements should focus on multimodal sensors, enhanced connectivity, and efficient power management to improve resilience and operational efficiency.

While the potential of AIoT in aquaculture is transformative, several limitations remain. High initial investment costs, the complexity of data infrastructure, and the demand for technical expertise create barriers, particularly for smaller operators. Concerns about data privacy and cybersecurity in interconnected systems pose significant challenges. Many AI models trained for specific species or environments lack the flexibility for broader applications, underscoring the need for adaptive AI solutions.

Observations from this review suggest that AIoT adoption thrives in environments that prioritize real-time monitoring, adaptive response mechanisms, and scalable infrastructure. Large-scale operations benefit from economies of scale, while smaller operators often face financial and technical hurdles. Bridging this gap will require cost-effective solutions, robust-edge computing systems, and accessible training resources for personnel.

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