Magna Scientia Advanced Biology and Pharmacy

eISSN: 2582-8363

Cross Ref DOI: 10.30574/msabp

Journal homepage: https://magnascientiapub.com/journals/msabp/

(Review Article)

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Exploring the role of IoT, AI, and remote sensing in precision aquaculture: Monitoring, automation, and data-driven decision-making

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Magna Scientia Advanced Biology and Pharmacy, 2025, 14(02), 018-033

Publication history: Received on 25 December 2024; revised on 24 February 2025; accepted on 27 February 2025

Article DOI: https://doi.org/10.30574/msabp.2025.14.2.0018

Abstract

Precision aquaculture is revolutionizing fish farming through the integration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and remote sensing. These innovations enhance real-time monitoring, automation, and data-driven decision-making, thereby improving efficiency, sustainability, and productivity. IoT-enabled sensors facilitate continuous tracking of critical environmental parameters, while AI-driven analytics optimize feed management, disease detection, and operational processes. Remote sensing complements these technologies by providing large-scale monitoring and environmental assessments, ensuring compliance with ecological and regulatory standards.

Despite these advancements, the widespread adoption of precision aquaculture faces challenges, including technical limitations, regulatory complexities, and high initial investment costs. However, emerging technologies such as edge computing and blockchain offer promising solutions to enhance system efficiency, transparency, and data security. Economic analyses highlight the long-term viability of these innovations, particularly in resource-limited settings where sustainable aquaculture can contribute to food security and economic growth.

This paper explores the synergy between IoT, AI, and remote sensing in precision aquaculture, analyzing case studies that demonstrate successful integration. It further examines policy and economic considerations essential for facilitating technology adoption and ensuring industry scalability. By addressing current challenges and leveraging future innovations, precision aquaculture has the potential to transform global seafood production, promoting sustainability while meeting the increasing demand for aquatic food resources.

Keywords: Precision aquaculture; Internet of Things (IoT); Artificial Intelligence (AI); Remote sensing; Sustainability; Fisheries management.

1. Introduction

1.1. Background and Importance

Precision aquaculture is an innovative approach that employs advanced technologies to enhance fish farming efficiency while promoting environmental sustainability. This methodology integrates various tools such as the Internet of Things (IoT), artificial intelligence (AI), and remote sensing, enabling real-time monitoring and precise control over aquaculture systems (Idoko et al., 2024). As the global demand for seafood continues to rise, the role of precision aquaculture in meeting production needs while reducing ecological impacts becomes increasingly critical. The strategic

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use of IoT facilitates the collection of detailed data on water quality parameters, such as pH, temperature, and oxygen levels, ensuring optimal conditions for fish health and growth (Bernal-Higuita & Acosta-Coll, 2023).

AI further enhances precision aquaculture by enabling predictive analytics and automation, which can optimize feeding schedules and detect diseases at early stages. This reduces waste, minimizes costs, and ensures the sustainable use of resources. Meanwhile, remote sensing technologies, including satellite imagery and drone-based monitoring, provide macro-level insights into environmental conditions, supporting site selection and habitat monitoring. Together, these technologies contribute significantly to reducing the environmental footprint of aquaculture, aligning with global sustainability goals (Gladju, Kamalam, & Kanagaraj, 2022).

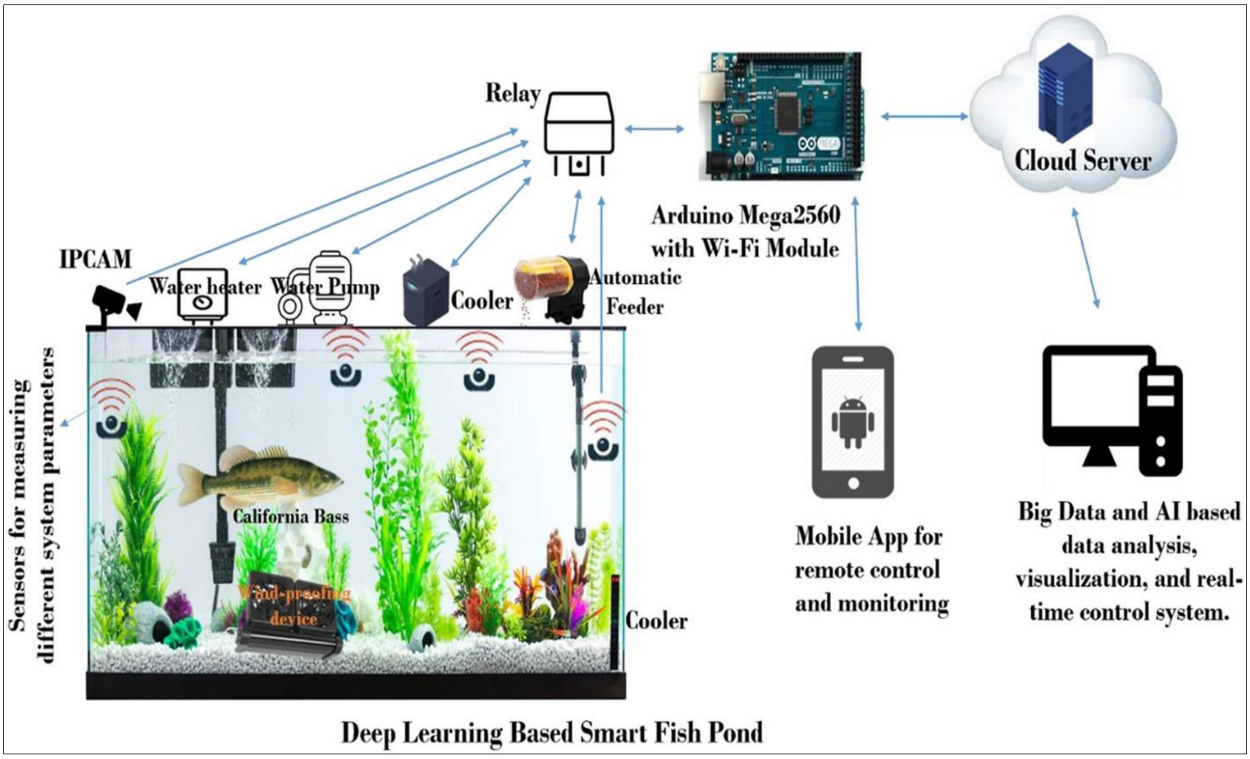

Figure 1 Smart Aquaculture System (Chiu et al., 2022)

The above image illustrates an integrated smart fish pond system featuring automated control mechanisms through Arduino, sensors, and cloud connectivity. It demonstrates how deep learning and IoT technologies work together to monitor and manage aquaculture parameters through mobile and desktop interfaces.

By integrating these technologies, precision aquaculture represents a transformative shift in fish farming practices, emphasizing sustainability and resilience. The application of these tools not only ensures higher yields but also mitigates adverse environmental effects, paving the way for a more sustainable future in seafood production (Mustapha et al., 2021).

1.2. Objective and Scope

The objective of this review is to delineate the transformative roles of the Internet of Things (IoT), Artificial Intelligence (AI), and remote sensing in advancing aquaculture practices. IoT serves as the backbone of data acquisition, enabling continuous real-time monitoring of critical parameters such as water quality, temperature, and fish health. This seamless connectivity and data flow provide aquaculture practitioners with actionable insights for system optimization. Similarly, AI processes these vast datasets, offering predictive analytics, early warnings, and tailored solutions for challenges like disease outbreaks and resource mismanagement. Remote sensing complements these technologies by providing large-scale environmental monitoring and spatial data, essential for site selection and ecosystem management.

The scope of these technologies extends across key areas of application: monitoring, automation, and data-driven decision-making. IoT technologies excel in monitoring by continuously tracking environmental and biological variables, which is vital for maintaining optimal aquaculture conditions. Meanwhile, AI-driven automation enhances operational efficiency by enabling automated feeding systems, behavioral analysis, and anomaly detection. Remote sensing technologies, such as satellite and drone-based imaging, offer a macro perspective, aiding in decision-making processes that involve assessing the suitability of aquaculture sites, predicting climate impacts, and managing ecological balance.

This review aims to explore the integration of these technologies in precision aquaculture, emphasizing their synergistic effects. By understanding their roles and applications, it becomes possible to unlock the full potential of these innovations in creating a sustainable, efficient, and resilient aquaculture industry. These advancements not only increase productivity but also contribute to global food security and environmental conservation.

1.3. Methodology

The methodology for this review involves a comprehensive examination of current literature and advancements related to the integration of IoT, AI, and remote sensing in precision aquaculture. Peer-reviewed articles, conference proceedings, and credible industry reports were analyzed to provide an extensive overview of how these technologies intersect and contribute to aquaculture practices. The selection criteria focused on works that highlight technological innovations, case studies, and critical evaluations of their impact on monitoring, automation, and decision-making within aquaculture systems (Chelladurai et al., 2024). The sources were meticulously assessed for relevance, credibility, and methodological rigor.

To establish a robust framework, the review employs a thematic analysis approach. This involves categorizing literature into key domains, such as monitoring systems enabled by IoT, AI-driven automation techniques, and remote sensing applications. The interconnectedness of these domains is examined to understand their collective contributions to enhancing aquaculture efficiency and sustainability. Furthermore, emphasis was placed on synthesizing insights into challenges and opportunities associated with these technologies, including scalability, cost-effectiveness, and environmental implications (Mandal & Ghosh, 2024). This approach enables the identification of knowledge gaps and potential areas for future research.

The review also incorporates case studies and empirical evidence to demonstrate practical implementations of these technologies. By evaluating real-world applications, this methodology ensures that the findings are grounded in actionable insights. This systematic and critical approach provides a holistic understanding of the transformative potential of IoT, AI, and remote sensing in advancing precision aquaculture (Mustapha et al., 2021).

2. Internet of Things (IoT) in Precision Aquaculture

2.1. IoT Fundamentals in Aquaculture

The Internet of Things (IoT) represents a transformative technology characterized by its ability to interconnect devices and enable seamless communication through the internet. In aquaculture, IoT systems comprise interconnected sensors, controllers, and communication networks that collect, analyze, and transmit real-time data (Idoko et al., 2024). This system is designed to automate processes and provide aquaculture practitioners with actionable insights, enhancing efficiency and productivity (Idoko et al., 2024). By leveraging IoT, aquaculture farms can maintain optimal environmental conditions, thereby improving fish health and reducing mortality rates.

IoT plays a pivotal role in aquaculture by enabling continuous monitoring of critical parameters, such as water quality, temperature, dissolved oxygen levels, and pH. Sensors deployed in aquaculture facilities collect data at regular intervals, transmitting this information to central systems for analysis. This real-time feedback allows farmers to respond promptly to environmental changes, ensuring a stable habitat for aquatic species. For instance, if oxygen levels drop below the threshold, automated aeration systems activated through IoT can restore balance, preventing potential losses (Mustapha et al., 2021). Furthermore, IoT enhances operational efficiency by enabling remote monitoring, reducing labor dependency, and minimizing manual errors.

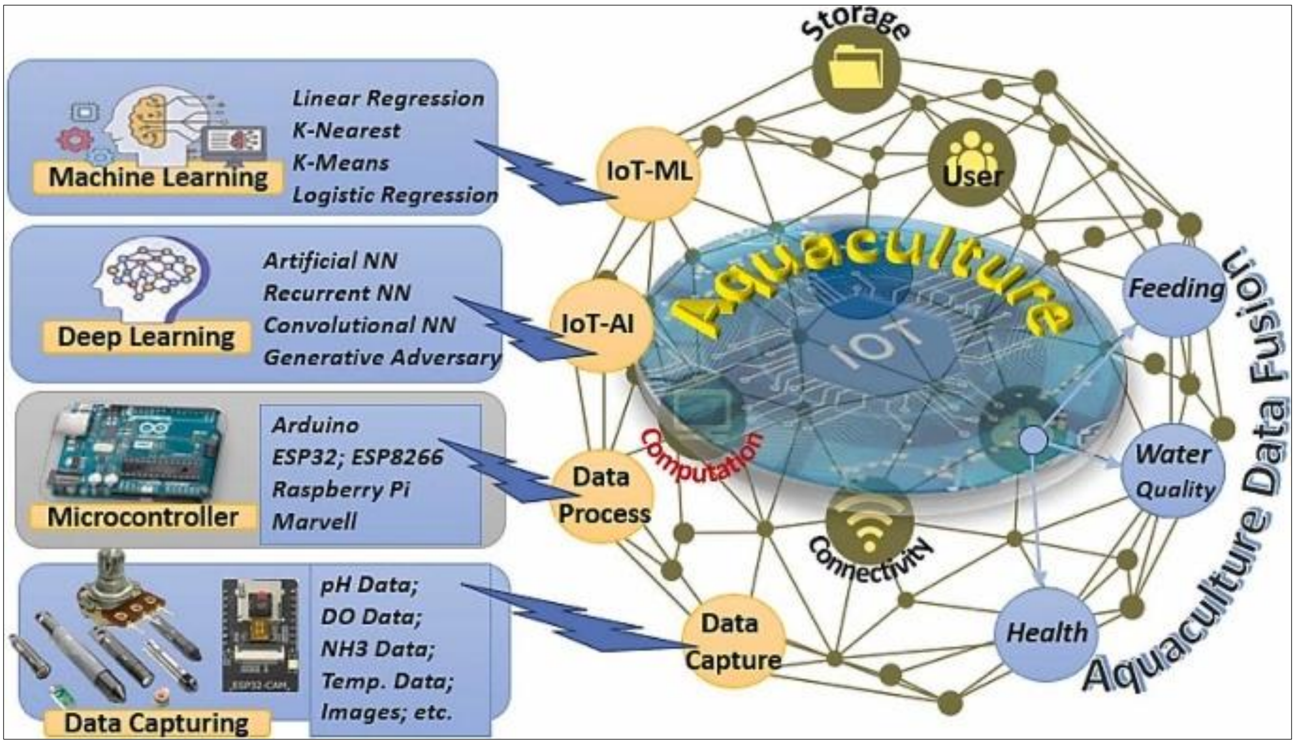

Figure 2 IoT-Enabled Smart Aquaculture Ecosystem (Abdullah et al., 2024)

This image outlines an integrated IoT ecosystem for aquaculture, showcasing how machine learning, deep learning, and microcontroller components interconnect with data capture systems to monitor and manage various aspects like water quality, feeding, and fish health.

The integration of IoT in aquaculture not only ensures precision farming but also supports sustainable practices. By providing detailed insights into resource usage, such as feed and water, IoT facilitates more informed decision-making, thereby reducing waste and environmental impacts. The system's capacity to collect and process vast amounts of data positions it as a cornerstone for the future of smart aquaculture, aligning with global sustainability goals (Mandal & Ghosh, 2024).

2.2. Applications of IoT

The applications of IoT in aquaculture are instrumental in achieving precision and sustainability in farming practices. One of the primary applications is water quality monitoring, which is vital for maintaining optimal living conditions for aquatic organisms. IoT-enabled sensors continuously measure parameters such as temperature, pH, salinity, and dissolved oxygen, transmitting data in real time to centralized systems. This facilitates proactive management of water quality, ensuring stability in aquaculture environments (Idoko et al., 2024). For example, when oxygen levels fall below the required threshold, automated aeration systems are activated, reducing stress and mortality in fish populations (Mandal & Ghosh, 2024). Such systems significantly enhance productivity and prevent costly losses, especially in intensive aquaculture setups.

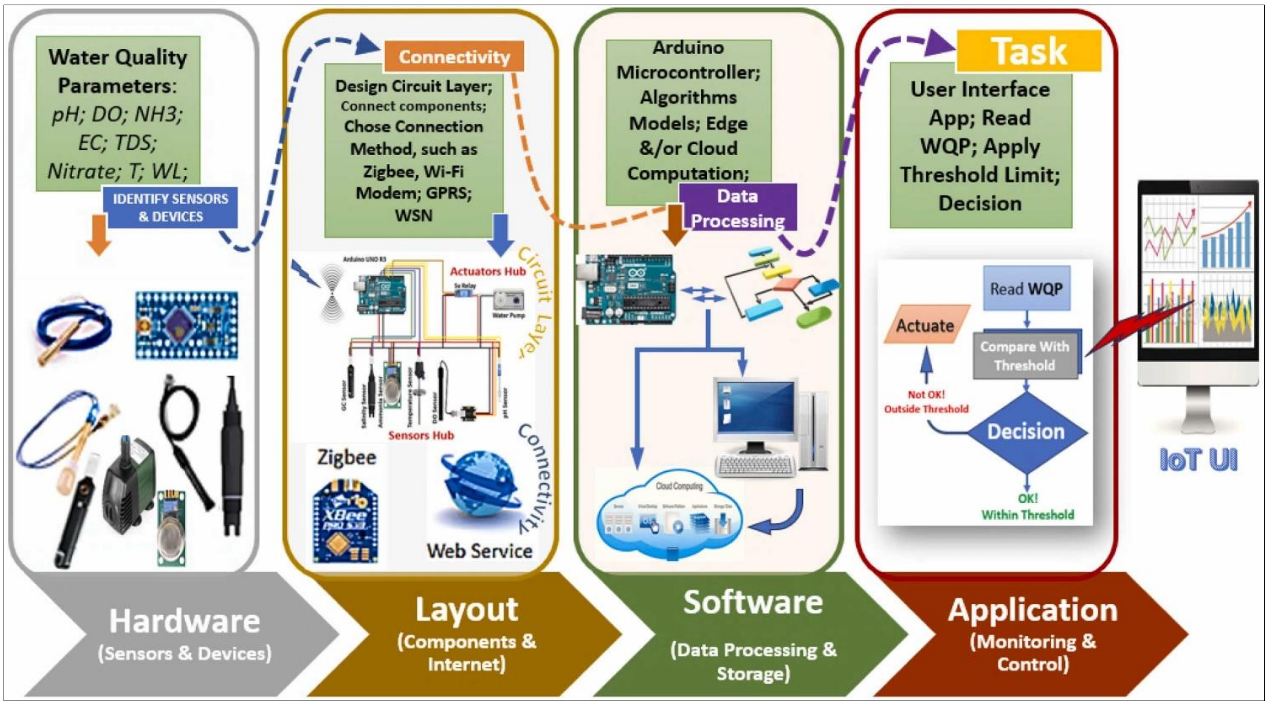

Figure 3 IoT Architecture for Smart Aquaculture Systems (Abdullah et al., 2024)

(Figure 3) illustrates a comprehensive IoT framework for aquaculture monitoring, showing the progression from hardware sensors through connectivity layout and software processing to application interface. It demonstrates how water quality parameters are monitored, processed, and analyzed for precise aquaculture management.

Fish health monitoring and behavioral analysis represent another critical application of IoT. Smart sensors and underwater cameras collect data on fish movements, feeding patterns, and health indicators. Advanced analytics and AI algorithms process this data, enabling early detection of diseases and abnormal behaviors. This capability allows farmers to address potential issues before they escalate, minimizing the spread of infections and reducing dependency on antibiotics (Mustapha et al., 2021). For instance, behavioral deviations such as erratic swimming patterns may signal oxygen deficiency or disease onset, prompting immediate corrective actions.

The integration of IoT into these applications underscores its transformative potential in aquaculture. By offering continuous monitoring and actionable insights, IoT enables farmers to optimize operations, reduce resource wastage, and ensure the well-being of aquatic species. This not only improves economic outcomes but also aligns aquaculture practices with environmental sustainability goals (Chelladurai et al., 2024).

2.3. Challenges and Opportunities

The integration of IoT in aquaculture faces several challenges, particularly concerning network infrastructure and scalability. Reliable connectivity is crucial for IoT systems to transmit data in real-time, but aquaculture farms, especially those in remote or offshore locations, often lack robust internet and communication networks. This limitation hampers the effectiveness of IoT-based monitoring and automation systems. Moreover, scaling IoT infrastructure to accommodate larger aquaculture operations increases the complexity of network management, including issues related to bandwidth, latency, and data security (Mandal & Ghosh, 2024). Overcoming these challenges requires investments in advanced communication technologies, such as satellite-based internet and edge computing, which can enhance connectivity and support real-time data processing.

Table 1 Roles, Challenges, and Opportunities of IoT Integration Framework in Aquaculture

Role	Challenges	Opportunities	Impacts
Infrastructure	Limited connectivity in remote locations; Network reliability issues; Bandwidth constraints	Implementation of satellite-based internet; Edge computing adoption; Advanced communication tech	Enhanced real-time monitoring; Improved data transmission; Better system reliability
Operations	Complex network management; Scalability issues; Data security concerns	Automated feeding systems; Predictive maintenance; Resource optimization	Reduced operational costs; Minimized equipment downtime; Efficient resource usage
Decision Making	Data processing limitations; Real-time analysis challenges	Actionable insights generation; Data-driven planning; Enhanced monitoring capabilities	Improved farm productivity; Better resource allocation; Informed strategic planning
Sustainability	Initial investment costs; Technology adaptation	Resource waste reduction; Energy efficiency; Automated monitoring	Sustainable farming practices; Reduced environmental impact; Better fish health management

Despite these challenges, IoT presents significant opportunities to reduce costs and improve farm efficiency in aquaculture. By enabling precise monitoring and automation, IoT minimizes resource wastage, particularly in feed and energy consumption, which are major operational costs in aquaculture. Automated systems, powered by IoT, can optimize feeding schedules based on real-time data, reducing overfeeding and ensuring better fish health (Mustapha et al., 2021). Furthermore, IoT-enabled predictive maintenance of equipment, such as aerators and water pumps, reduces downtime and repair costs, contributing to overall efficiency.

The opportunities offered by IoT also extend to improved decision-making and scalability. By providing actionable insights through real-time data analytics, IoT enables aquaculture practitioners to make informed decisions, enhancing productivity and sustainability. This potential for cost reduction and efficiency improvement underscores the transformative role of IoT in addressing the growing demand for sustainable seafood while overcoming current infrastructural limitations (Chelladurai et al., 2024).

3. Artificial Intelligence (AI) in Precision Aquaculture

3.1. AI Techniques and Models

Artificial intelligence (AI) has emerged as a transformative tool in aquaculture, leveraging advanced computational techniques to address complex challenges. Key AI methodologies used in aquaculture include machine learning (ML) and deep learning (DL). Machine learning, a subset of AI, employs algorithms that enable systems to learn from data and improve their performance over time without explicit programming. Applications of ML in aquaculture range from predicting water quality variations to optimizing feeding schedules based on fish behavior and environmental conditions (Idoko et al., 2024). These techniques rely on historical data to develop models capable of making accurate predictions, facilitating informed decision-making.

Deep learning, a more advanced subset of machine learning, utilizes artificial neural networks that mimic the human brain's structure and function. These networks excel at processing large, unstructured datasets, such as images and videos, making them particularly useful in aquaculture for tasks like fish health monitoring and behavior analysis. For example, convolutional neural networks (CNNs) are employed to analyze underwater images for detecting disease symptoms or estimating fish size, while recurrent neural networks (RNNs) are used for time-series analysis of environmental data (Mustapha et al., 2021). These applications not only enhance operational efficiency but also contribute to the early detection of potential issues, reducing losses and promoting sustainability.

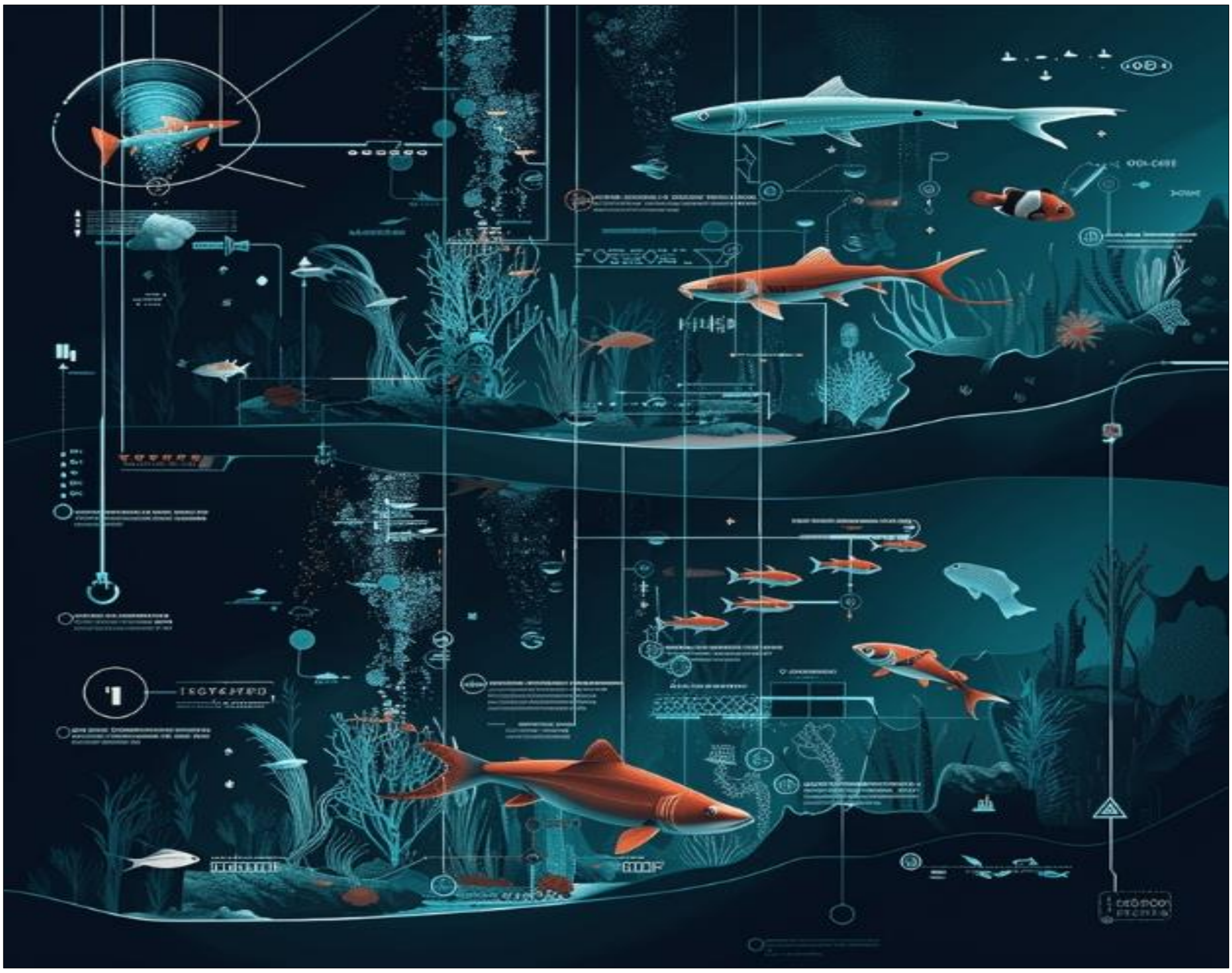

Figure 4 Digital Ecosystem Mapping (ANACEA Logistics Technology Solutions, 2024)

The image above depicts an intricate technical blueprint of an aquatic ecosystem, overlaid with digital metrics and monitoring systems. It illustrates how AI and machine learning technologies integrate with aquaculture, tracking fish behavior, health, and environmental conditions in real-time.

The adoption of AI methodologies in aquaculture signifies a paradigm shift towards precision farming. By integrating machine learning and deep learning models, aquaculture practitioners can achieve real-time monitoring, predictive analytics, and automation. This fosters sustainable practices while maximizing productivity, underscoring the critical role of AI in advancing the aquaculture industry (Chelladurai et al., 2024).

3.2. Applications of AI

Artificial intelligence (AI) is revolutionizing aquaculture by addressing key challenges through its advanced applications. One of the most critical areas is disease prediction and early detection. AI utilizes image and sensor data to identify patterns indicative of health issues in aquatic organisms. For instance, computer vision algorithms analyze fish images to detect physical abnormalities, while sensor data is employed to monitor environmental conditions that may contribute to disease outbreaks (Mandal & Ghosh, 2024). This capability enables farmers to implement timely interventions, minimizing losses and reducing the need for antibiotics, which aligns with sustainable farming practices.

Figure 5 The Future of Smart Fish Farming through AI-Powered Aquaculture (Shannak,2024)

The image illustrates how AI transforms modern aquaculture through integrated technology. This representation demonstrates the role of AI in revolutionizing aquaculture management, disease detection, and sustainable farming practices.

AI also plays a significant role in feed optimization, a critical component of cost-effective aquaculture. Behavioral analysis, facilitated by AI-driven models, helps in determining the precise quantity and timing of feed delivery based on real-time monitoring of fish activity. For example, machine learning models analyze movement patterns and feeding behaviors to ensure optimal feed utilization while avoiding wastage (Idoko et al., 2024). This not only enhances fish growth but also reduces the environmental impact of overfeeding, such as nutrient pollution in water bodies.

Another transformative application of AI in aquaculture is predictive analytics for yield estimation and decision-making. By processing historical and real-time data, AI models predict growth rates, harvest timings, and potential yields with high accuracy. These insights empower farmers to make informed decisions regarding resource allocation, production planning, and market readiness (Chelladurai et al., 2024). Additionally, predictive analytics assists in identifying risks, such as adverse environmental changes, enabling proactive measures that safeguard aquaculture operations.

3.3. Challenges in AI Adoption

The adoption of artificial intelligence (AI) in aquaculture faces significant challenges, particularly in the areas of data availability and quality. AI systems rely heavily on large datasets for training and decision-making, but the aquaculture sector often lacks comprehensive and standardized data. Variations in data collection methods, limited access to historical datasets, and inconsistencies in sensor accuracy impede the development of robust AI models (Mandal & Ghosh, 2024). Additionally, the dynamic nature of aquaculture environments demands high-quality, real-time data for effective implementation, which can be costly and technically challenging to acquire. Addressing these issues requires the establishment of standardized protocols for data collection and the adoption of advanced technologies for real-time data acquisition.

Ethical and regulatory considerations also pose challenges to AI adoption in aquaculture. The use of AI for decision-making raises concerns about accountability, particularly when errors or unintended outcomes occur. For instance, reliance on AI-generated predictions for disease management or feed optimization could lead to economic losses or environmental harm if the algorithms are flawed or misinterpreted (Mustapha et al., 2021). Moreover, there is a need for clear regulatory frameworks to govern the deployment of AI technologies, ensuring transparency, fairness, and compliance with environmental and animal welfare standards. Ethical concerns surrounding data privacy and ownership also emerge, especially in collaborative aquaculture projects that involve multiple stakeholders.

Table 2 Key Stakeholder Roles in AI Adoption for Aquaculture

Role/Aspect	Challenges	Impact	Solutions
Data Scientists & Engineers	- Limited availability of standardized data - Inconsistent data collection methods - Sensor accuracy issues - Need for real-time data processing	- Difficulty in developing reliable AI models - Increased costs for data acquisition - Technical limitations in implementation	- Establish standardized data collection protocols - Implement advanced sensing technologies - Develop robust data infrastructure
Policymakers & Regulators	- Lack of clear regulatory frameworks - Need for governance structures - Accountability concerns - Data privacy issues	- Uncertainty in compliance requirements - Challenges in enforcement - Risk of unregulated AI deployment	- Create comprehensive regulatory frameworks - Develop transparency guidelines - Establish accountability measures
Aquaculture Practitioners	- High implementation costs - Technical complexity - Risk of AI-related errors - Integration with existing systems	- Potential economic losses - Environmental risks - Operational disruptions	- Training and capacity building - Gradual technology adoption - Risk management strategies
Technology Developers	- Complex environmental variables - Need for robust algorithms - Integration challenges - Stakeholder collaboration	- Development constraints - Market adoption barriers - Resource requirements	- Cross-sector collaboration - Adaptive technology solutions - User-friendly interfaces

These challenges highlight the need for a multidisciplinary approach to AI adoption in aquaculture. By improving data infrastructure, fostering transparency, and developing ethical guidelines, the sector can harness the transformative potential of AI while mitigating associated risks. Collaborative efforts between technology developers, policymakers, and aquaculture practitioners are essential to overcome these barriers and unlock the full benefits of AI in sustainable aquaculture practices (Chelladurai et al., 2024).

4. Role of Remote Sensing in Aquaculture

4.1. Introduction to Remote Sensing

Remote sensing technologies have become integral to precision aquaculture, offering powerful tools for large-scale environmental monitoring and resource management. Satellite-based remote sensing provides high-resolution spatial data on water bodies, such as temperature, turbidity, and chlorophyll concentration, which are crucial indicators of aquatic health and productivity (Mandal & Ghosh, 2024). Similarly, drones equipped with advanced imaging sensors enable detailed and localized observations, capturing data on fish behavior, vegetation coverage, and habitat conditions. These technologies enhance the ability of aquaculture practitioners to make informed decisions by providing a comprehensive view of environmental factors that influence aquaculture operations.

The synergy between remote sensing and in-situ IoT data significantly amplifies the effectiveness of aquaculture management. While satellite and drone-based technologies provide macroscopic insights, IoT systems deliver high-resolution, real-time data from sensors deployed within aquaculture environments (Chelladurai et al., 2024). For example, IoT sensors measure parameters such as dissolved oxygen and pH at specific depths, complementing the broader environmental data collected through remote sensing. This integration allows for cross-validation of data, improving the accuracy and reliability of predictions and analyses. Such hybrid approaches ensure that aquaculture practices remain adaptive and responsive to dynamic environmental conditions.

By combining remote sensing with IoT, aquaculture systems can achieve unprecedented levels of precision and efficiency. This integrated approach supports sustainable practices by minimizing environmental impacts and optimizing resource utilization. Moreover, it facilitates proactive risk management, such as identifying algal blooms or detecting changes in water quality before they affect aquaculture yields. As these technologies continue to advance, their role in transforming aquaculture into a data-driven and sustainable industry is expected to grow substantially (Idoko et al., 2024).

4.2. Applications of Remote Sensing

Remote sensing has become an invaluable tool in aquaculture for mapping and monitoring aquaculture sites, as well as assessing environmental impacts and monitoring habitats. By utilizing technologies such as satellite imaging and drone-based systems, aquaculture practitioners can identify optimal locations for aquaculture activities, monitor ongoing operations, and detect changes in land use and water quality. These methods facilitate the creation of detailed maps that illustrate aquaculture boundaries, environmental conditions, and the spatial distribution of aquaculture facilities (Rajitha et al., 2007). The integration of Geographic Information Systems (GIS) further enhances the utility of remote sensing by enabling the analysis of spatial and temporal data, thus supporting effective decision-making.

In terms of environmental impact assessment, remote sensing aids in detecting changes in coastal and aquatic habitats caused by aquaculture activities. This includes monitoring the conversion of natural ecosystems, such as mangroves, into aquaculture ponds, which has significant implications for biodiversity and ecosystem services. For instance, studies in coastal regions of India demonstrated how remote sensing could track mangrove loss and assess its correlation with aquaculture expansion, providing critical insights for sustainable management practices (Pattanaik & Prasad, 2011). Furthermore, such data supports environmental policies aimed at minimizing the adverse impacts of aquaculture on sensitive ecosystems.

Table 3 Remote Sensing Roles and Responsibilities in Aquaculture Management

Role	Responsibilities	Tools & Technologies	Applications & Outcomes
Environmental Scientists	- Monitor ecosystem changes - Assess environmental impacts - Track habitat modifications - Analyze water quality	- Satellite imaging systems - Environmental sensors - GIS analysis tools - Water quality monitors	- Ecosystem impact reports - Habitat conservation strategies - Environmental compliance monitoring - Biodiversity assessments
Aquaculture Managers	- Site selection - Operation monitoring - Compliance management - Resource allocation	- Drone-based systems - Mapping software - Real-time monitoring tools - Decision support systems	- Optimal site identification - Operational efficiency - Regulatory compliance - Sustainable management practices
Data Analysts	- Data processing - Spatial analysis - Temporal tracking - Pattern identification	- GIS software - Data visualization tools - Analysis platforms - Mapping applications	- Detailed site maps - Trend analysis - Change detection reports - Decision support information

Policy Makers	- Standard setting - Regulation development - Impact assessment - Conservation planning	- Monitoring frameworks - Policy tools - Assessment guidelines - Compliance systems	- Environmental policies - Conservation strategies - Management guidelines - Sustainability frameworks

Remote sensing also plays a pivotal role in habitat monitoring by offering high-resolution imagery to assess water quality, sedimentation patterns, and other environmental parameters critical for aquaculture sustainability. These capabilities enable continuous monitoring of aquaculture operations and surrounding habitats, ensuring compliance with environmental standards and supporting proactive management approaches. As aquaculture continues to expand globally, the synergy between remote sensing, GIS, and other advanced technologies holds immense potential for fostering sustainable practices while mitigating ecological risks (Ottinger et al., 2016).

4.3. Challenges and Integration

The integration of remote sensing in aquaculture faces several challenges, including technical limitations such as data resolution and processing capabilities. High-resolution imagery is often critical for accurate monitoring and decision-making, but the associated costs and computational demands can be prohibitive. Moreover, the processing of large volumes of satellite or drone data requires sophisticated algorithms and computing infrastructure, which are often unavailable in many aquaculture operations. These barriers limit the scalability and widespread adoption of remote sensing technologies in aquaculture, especially in developing regions where resources are constrained (Gladju et al., 2022).

Despite these challenges, opportunities for integrating remote sensing with Internet of Things (IoT) and Artificial Intelligence (AI) technologies offer promising solutions. IoT-enabled devices can complement remote sensing by providing real-time, in situ data on water quality and environmental conditions, bridging gaps in temporal and spatial resolution. AI algorithms, when paired with remote sensing and IoT data, can enhance the accuracy of predictive models for aquaculture management, including disease outbreak forecasts and feed optimization strategies. Such synergies enable smarter, more efficient aquaculture systems, fostering sustainability and productivity in the sector (Rastegari et al., 2023).

Table 4 Stakeholder Roles in Aquaculture Technology Integration

Role/Aspect	Challenges	Opportunities	Solutions & Innovations
Technical Engineers	- Limited data resolution - High computational demands - Processing infrastructure needs - Resource constraints	- IoT integration possibilities - AI algorithm development - Advanced processing systems - Real-time monitoring capabilities	- Development of efficient algorithms - Implementation of scalable systems - Integration of IoT devices - Enhanced processing solutions
Data Scientists	- Complex data processing needs - Algorithm development challenges - Integration of multiple data sources - Model accuracy requirements	- AI/ML model development - Predictive analytics - Pattern recognition systems - Data fusion opportunities	- Advanced predictive models - Disease outbreak forecasting - Feed optimization systems - Automated analytics tools
Aquaculture Managers	- High technology costs - Implementation challenges	- Precision farming adoption	- Smart management systems - Automated control mechanisms

	- Training requirements - Resource allocation	- Automated management systems - Resource optimization - Environmental monitoring	- Resource efficiency tools - Environmental impact reduction
System Integrators	- Technology compatibility issues< - Infrastructure limitations - Scalability challenges - Implementation barriers	- System integration possibilities - Cross-platform solutions - Automated workflows - Sustainable practices	- Integrated monitoring systems - Cross-platform compatibility- Scalable solutions - Sustainable technology implementation

Additionally, the integration of these technologies can drive innovation in aquaculture, paving the way for precision farming approaches. By combining remote sensing data with AI-driven analytics, aquaculture managers can develop automated systems capable of optimizing resource use while minimizing environmental impacts. These advancements underscore the transformative potential of technology to address key challenges in aquaculture and support sustainable practices on a global scale (Senoo et al., 2024).

5. Integration and Future Directions

5.1. Synergy between IoT, AI, and Remote Sensing

The synergy between the Internet of Things (IoT), Artificial Intelligence (AI), and remote sensing has proven transformative for precision aquaculture. These technologies work in tandem to provide comprehensive monitoring, predictive analytics, and automation for aquaculture systems. A notable case study highlights an integrated framework in Southeast Asia that employs IoT-enabled sensors to continuously monitor water quality parameters, AI algorithms for predictive disease modeling, and remote sensing for spatial analysis of aquaculture sites. This approach not only enhanced operational efficiency but also reduced environmental impacts by optimizing feed usage and mitigating water pollution.

Frameworks that combine these technologies emphasize data-driven decision-making and sustainable practices. For instance, a recent AI-driven IoT platform incorporates satellite-based remote sensing data with in-situ sensor readings to create a holistic aquaculture management system. This platform allows for real-time monitoring and adaptive management of fish farms, addressing challenges like fluctuating environmental conditions and disease outbreaks. The integration of predictive AI models ensures that farmers can anticipate and address potential issues, thereby improving yield and reducing costs.

These synergies also support scalable solutions for global aquaculture. By leveraging AI-enhanced frameworks, small-scale aquaculture practitioners can access advanced tools that were once limited to large industrial setups. Such frameworks are crucial for addressing food security challenges and promoting sustainable aquaculture development worldwide. As the adoption of IoT, AI, and remote sensing grows, future frameworks are expected to incorporate blockchain for traceability and advanced machine learning models for even greater precision and efficiency.

5.2. Future Trends and Innovations

Emerging technologies such as edge computing and blockchain are poised to revolutionize aquaculture, driving the sector toward greater automation and intelligence. Edge computing, which processes data closer to the data source, addresses latency issues associated with cloud computing and enhances the real-time capabilities of aquaculture systems. This is particularly important for applications like water quality monitoring and automated feeding, where timely decisions are critical. Blockchain technology further augments this ecosystem by ensuring traceability, transparency, and security in aquaculture operations. For instance, blockchain can track the entire lifecycle of farmed fish, from hatchery to market, ensuring compliance with sustainability standards and building consumer trust.

The vision for fully automated and intelligent aquaculture systems incorporates these innovations to create self-regulating, adaptive environments. AI-powered platforms, integrated with IoT and edge computing, are capable of continuously learning and optimizing processes such as feeding schedules, water filtration, and disease prevention. By utilizing blockchain, these systems also enable seamless integration of supply chain data, reducing inefficiencies and enhancing profitability. A study demonstrated how a hybrid edge-cloud architecture successfully managed large-scale aquaculture farms, achieving significant cost reductions and environmental benefits while maintaining operational efficiency.

The future of aquaculture lies in integrating these technologies into a cohesive framework that supports precision farming. The adoption of cloud-edge collaborations, AI analytics, and blockchain-driven transparency can enable sustainable practices and scalability in aquaculture. With continuous advancements, these technologies are expected to deliver highly efficient, environmentally friendly aquaculture systems capable of meeting global food security demands.

5.3. Policy and Economic Considerations

The implementation of effective regulatory frameworks is critical to fostering the adoption of advanced technologies in aquaculture while ensuring environmental sustainability and economic viability. These frameworks must address key areas such as licensing, environmental impact assessments, and the standardization of practices for technology adoption. A predictable and well-defined regulatory environment not only encourages investment but also minimizes conflicts between stakeholders, including governments, private enterprises, and local communities. Clear regulations reduce uncertainties, fostering greater innovation and the integration of technologies such as IoT and AI in aquaculture systems.

Economic sustainability in aquaculture depends on thorough cost-benefit analyses that evaluate the feasibility of adopting new technologies. Such analyses consider the upfront costs of infrastructure and technology against long-term gains in productivity, resource efficiency, and environmental compliance. The benefits of adopting precision aquaculture technologies outweighed the costs, particularly in improving water use efficiency and reducing feed wastage. These findings highlight the role of technology in enhancing the economic resilience of aquaculture ventures, particularly in resource-limited settings.

Policymakers must also consider broader socio-economic implications, including job creation and food security. Integrating technology into rural aquaculture systems has the potential to transform livelihoods and contribute to sustainable development goals. However, this requires investments in capacity building and infrastructure to ensure that small-scale operators can participate equitably in technology-driven aquaculture markets. Balancing these considerations is key to promoting a sustainable and inclusive aquaculture sector that meets global demands while conserving natural resources.

6. Conclusion

Precision aquaculture represents a transformative approach to sustainable aquaculture practices, leveraging advanced technologies such as IoT, AI, and remote sensing. These tools have demonstrated significant potential in improving efficiency, reducing environmental impacts, and enhancing decision-making processes. The integration of IoT enables real-time monitoring of critical parameters such as water quality and fish health, while AI facilitates predictive analytics and automated systems that optimize feeding, disease management, and resource allocation. The use of remote sensing further supports large-scale monitoring and environmental assessments, offering a comprehensive framework for managing aquaculture systems.

While these advancements offer substantial benefits, challenges remain, including the need for robust regulatory frameworks and overcoming technical barriers such as data processing and infrastructure limitations. Economic sustainability also depends on detailed cost-benefit analyses that justify the investment in precision technologies. Nonetheless, the synergy between IoT, AI, and remote sensing holds immense potential to reshape aquaculture into a more sustainable and scalable sector. Case studies have highlighted the feasibility of these technologies in enhancing productivity and ensuring compliance with environmental and regulatory standards, particularly in resource-constrained regions.

In conclusion, advancing precision aquaculture requires a multidisciplinary approach that combines technological innovation, policy support, and economic investment. Stakeholders, including governments, industry players, and researchers, must collaborate to address the existing challenges and unlock the full potential of these technologies. By prioritizing sustainable practices and equitable access to advanced systems, precision aquaculture can play a critical role in meeting the global demand for seafood while conserving natural ecosystems for future generations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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