

Review Article

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Study on the Application Effects of Digital Monitoring in Ecological Pond Aquaculture

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Abstract Ecological pond aquaculture is an important model for promoting the green, standardized, and intelligent development of aquaculture. However, traditional pond management still faces problems such as low efficiency of manual inspection, delayed identification of water quality changes, insufficient disease early-warning capacity, and low resource utilization efficiency. Through sensors, the Internet of Things, cloud platforms, intelligent control, and data analysis, digital monitoring technology can conduct real-time collection and dynamic analysis of key water quality indicators, including water temperature, dissolved oxygen, pH, ammonia nitrogen, nitrite, and turbidity, thereby providing continuous, accurate, and traceable data support for ecological pond aquaculture. This study analyzes the application contents and effects of digital monitoring in ecological pond aquaculture, with a focus on its roles in real-time monitoring of water quality and environmental conditions, intelligent aeration and feeding management, disease early warning, and production process traceability. Digital monitoring helps improve water quality regulation efficiency, reduce management costs such as manual pond inspection, energy consumption, and feed waste, enhance the controllability of the aquaculture process, and promote improvements in aquaculture yield and product quality. However, the current application of digital monitoring still faces challenges, including high equipment investment and maintenance costs, insufficient data accuracy and system stability, and limited digital application capacity among aquaculture operators. In the future, the application pathway of digital monitoring should be optimized by improving equipment configuration, establishing scientific data management and early-warning mechanisms, and strengthening technical training and extension services, so as to promote ecological pond aquaculture toward precision, intelligence, and sustainability.

Keywords Digital monitoring; Ecological pond aquaculture; Water quality regulation; Intelligent aeration; Smart fishery

1 Introduction

Pond aquaculture is an important component of aquaculture in China and plays a significant role in ensuring the supply of aquatic products, increasing farmers' income, and promoting rural industrial development. Ecological pond aquaculture, developed on the basis of traditional pond aquaculture, further emphasizes resource conservation, environmental protection, and ecological coordination. Previous studies have pointed out that traditional pond management often relies on manual inspection, low-frequency measurements, and farmers' experience, making it difficult to meet the requirements of modern aquaculture for efficiency, stability, and sustainability (Henares et al., 2020; Liu et al., 2020). With the growing demand for aquatic products, traditional pond aquaculture is also facing problems such as frequent water quality fluctuations, relatively high stocking density, increased disease risks, and low efficiency of manual management. Therefore, against the background of increasing environmental regulatory pressure and rising market demand for high-quality and safe aquatic products, integrating digital monitoring technology into ecological pond systems has become an important direction for promoting the green, standardized, and intelligent development of pond aquaculture (Kanwal et al., 2024).

In recent years, the application of digital monitoring technology in aquaculture has continued to expand. Internationally, many studies have applied IoT sensors, wireless sensor networks, automatic control systems, cloud platforms, and mobile applications to real-time water quality monitoring in ponds or aquaculture tanks, with a focus on key indicators such as pH, temperature, and dissolved oxygen, so as to achieve remote supervision and dynamic management (Lin et al., 2021). Relevant reviews have shown that IoT-based aquaculture monitoring

studies have increased rapidly since 2018, and inland pond aquaculture has become one of the main application scenarios (Flores-Iwasaki et al., 2025). Meanwhile, machine learning, fuzzy logic, and quantum-inspired optimization methods have gradually been applied to water quality prediction, equipment control, and climate-adaptive management, indicating that digital monitoring has become an important technical support for the transformation of modern aquaculture management models (Nagothu et al., 2024; Hemal et al., 2024).

In China, pond aquaculture is an important foundation of aquatic product production, but it also faces practical challenges such as water quality deterioration, high emission loads, declining product quality, and increasing aquaculture environmental risks. Therefore, ecological engineering and green development have received increasing attention. Ecological pond aquaculture requires whole-process refined management in terms of rational stocking, scientific feeding, water quality regulation, tailwater treatment, and ecological restoration. Previous studies have emphasized that promoting pond ecological engineering from a whole-process perspective is of great significance for improving pond environments, enhancing resource utilization efficiency, and promoting the sustainable development of aquaculture (Liu et al., 2020). However, existing studies on digital monitoring have mostly focused on general aquaculture systems or intensive aquaculture scenarios, while relatively few studies have explicitly linked real-time monitoring performance with the operational effects of ecological ponds (Henares et al., 2020). Although some digital systems have verified their technical feasibility and measurement accuracy, systematic evaluation of their application effects under local aquaculture conditions and specific management practices remains insufficient (Huan et al., 2020; Prapti et al., 2021).

This study will explore the application effects of digital monitoring in ecological pond aquaculture, focusing on its roles in water quality regulation, intelligent aeration, precision feeding, disease early warning, cost control, and product quality improvement, and further discuss the problems and optimization strategies in its promotion and application. The application of digital monitoring in ecological pond aquaculture is not only an update of technical tools, but also a transformation of aquaculture management methods. Through online monitoring equipment and data management platforms, aquaculture operators can promptly understand changes in pond water quality and environmental conditions, thereby reducing the uncertainty caused by sole reliance on empirical judgment. Previous studies have indicated that continuous and accurate sensing and data-driven control help improve water quality stability, reduce environmental loads, and enhance the operational performance of aquaculture systems. This study aims to provide references for innovation in ecological pond aquaculture management models and the construction of smart fisheries, as well as theoretical support and practical guidance for the transformation of pond aquaculture from experience-based management to data-driven management.

2 Overview of Ecological Pond Aquaculture and Digital Monitoring Technologies

2.1 Basic Connotation of Ecological Pond Aquaculture

Ecological pond aquaculture is a green, intensive, and sustainable aquaculture model developed on the basis of traditional pond aquaculture. Its core lies in achieving coordination between aquaculture production and ecological environmental protection by optimizing aquaculture structure, improving the water environment, and enhancing resource utilization efficiency. Compared with traditional aquaculture methods that simply pursue high density and high yield, ecological pond aquaculture places greater emphasis on environmental sustainability, resource utilization efficiency, and ecosystem service functions, rather than yield maximization driven by a single factor. Previous studies have pointed out that the expansion of intensive pond aquaculture has led to increased water consumption, water quality deterioration, aquaculture tailwater pollution, and declining product quality, all of which restrict the sustainable development of major aquaculture countries such as China (Liu et al., 2020). Therefore, ecological pond aquaculture does not simply mean reducing aquaculture intensity; rather, it uses ecological engineering approaches to improve animal welfare, stabilize water treatment processes, and reduce the negative impacts of aquaculture activities on the environment and public health while maintaining production capacity.

From the perspective of aquaculture system composition, an ecological pond is not only a space for the growth of aquatic animals, but also a complex ecosystem composed of water, sediment, microorganisms, aquatic plants, plankton, and cultured organisms. In this system, water quality conditions, nutrient cycling, dissolved oxygen variation, algal community structure, and microbial community status directly affect feeding, growth, disease resistance, and survival of cultured organisms. One of the core concepts of ecological pond aquaculture is to use ecological processes and biodiversity to improve productivity while reducing ecological disservices such as pollution. Henares et al. (2020) defined ecological intensification in fish farming as the use of ecological processes and functions to improve productivity, enhance ecosystem services such as nutrient cycling and water self-purification, and reduce negative effects such as pollution. Therefore, ecological pond aquaculture requires operators not only to focus on stocking, feeding, and harvesting, but also to manage pond environments throughout the whole process from the perspectives of ecological balance and system regulation.

Ecological pond aquaculture usually adopts integrated aquaculture or multi-trophic utilization concepts rather than monoculture. Relevant strategies include integrated multi-trophic aquaculture, aquaculture-agriculture integrated systems, recirculating aquaculture systems, and biofloc technology, all of which aim to improve nutrient utilization efficiency and reduce waste generation (Henares et al., 2020). For example, regulating the carbon-nitrogen ratio of water to promote the formation of bioflocs and biofilms, increasing submerged attachment surfaces, and configuring species occupying different niches in the food web can increase the proportion of nutrients ultimately converted into harvested products while taking social, economic, and environmental sustainability into account. Pond cascade systems can also achieve nutrient retention, natural zooplankton succession, water self-purification, and multiple stocking-harvesting cycles, thereby making positive contributions to landscape sustainability (Kajgrová et al., 2023). Therefore, the basic goals of ecological pond aquaculture are stable and efficient production, quality and safety, and environmental friendliness. In essence, it represents a systematic transformation of pond aquaculture concepts, management technologies, and production models.

2.2 Main Types of Digital Monitoring Technologies

Digital monitoring technology refers to a technical system that uses sensors, the Internet of Things, automatic control, data platforms, and intelligent terminals to conduct real-time collection, transmission, analysis, and management of pond aquaculture environments and production processes. In ecological pond aquaculture, water quality monitoring is the most basic and critical application type, mainly including continuous monitoring of indicators such as water temperature, dissolved oxygen, pH, ammonia nitrogen, nitrite, turbidity, electrical conductivity, salinity, and water level. A review of IoT applications in aquaculture shows that temperature, dissolved oxygen, and pH are the most emphasized parameters in water quality monitoring frameworks (Prapti et al., 2021). Flores-Iwasaki et al. (2025) further found in a systematic review of IoT sensors in aquaculture systems that approximately 98% of studies monitored pH, 93% monitored temperature, and 63% monitored dissolved oxygen, often combined with comprehensive monitoring of turbidity, total dissolved solids, salinity, water level, and other indicators. These technologies can transform water quality changes that originally relied on empirical judgment into recordable, comparable, and analyzable data, thereby providing an intuitive basis for aquaculture management.

In addition to water quality monitoring, equipment operation monitoring and intelligent control are also important components of digital monitoring. In specific applications, NB-IoT-based pond monitoring systems can measure temperature, pH, and dissolved oxygen through STM32 microcontrollers and upload data to telecom cloud platforms, supporting centralized management and intelligent control of aerators and other equipment. Wireless multi-sensor systems can integrate temperature, pH, dissolved oxygen, and electrical conductivity sensors with ESP32 Wi-Fi modules, and transmit data to cloud-based IoT platforms such as ThingSpeak and mobile applications (Lin et al., 2021). Low-cost designs can also use ESP8266 or Arduino platforms combined with pH, temperature, and total dissolved solids sensors to provide relatively economical and reliable real-time monitoring solutions for small-scale or rural ponds (Subowo and Pradita, 2025). These systems can automatically control the

start and stop of aerators according to changes in dissolved oxygen, adjust feeding plans based on water temperature, weather, and feeding behavior of cultured organisms, and monitor the operating status of water pumps, valves, power supply equipment, and other facilities, thereby improving the timeliness, precision, and automation level of pond management.

In addition, video monitoring, meteorological monitoring, production data management, and intelligent decision-making technologies are gradually being applied in ecological pond aquaculture. Video monitoring can assist in observing the activity status, feeding behavior, and abnormal pond conditions of cultured organisms; meteorological monitoring can provide reference for judging risks such as hypoxia, stress, and abrupt water quality changes; production data management can record seedling stocking, feed use, medication, water quality changes, and product harvest information, providing support for production process traceability and quality and safety management. More advanced smart aquaculture solutions further combine the Internet of Things with fuzzy logic, machine learning, and other methods for autonomous control and predictive analysis of pond environments (Kanwal et al., 2024). Together, these technologies constitute a multi-level application system of digital monitoring in ecological pond aquaculture, enabling aquaculture management to gradually expand from single water quality detection to environmental perception, equipment control, risk warning, and production decision-making.

2.3 Operating mechanism of digital monitoring systems

The operating mechanism of digital monitoring systems usually includes data collection, data transmission, data analysis, early-warning feedback, and equipment linkage. From the perspective of technical architecture, digital monitoring systems in ecological ponds generally follow a layered structure from the perception layer to the network layer, platform layer, and application layer. At the perception layer, underwater or in situ sensors deployed in ponds continuously measure water parameters such as pH, water temperature, dissolved oxygen, turbidity, electrical conductivity, salinity, and water level (Flores-Iwasaki et al., 2025). Sensor output signals are usually collected by microcontrollers such as STM32, Arduino, ESP32, or ESP8266, which complete signal conditioning, pre-calibration, in situ calibration, and preliminary processing (Shete et al., 2024). Compared with traditional manual testing, digital acquisition has the advantages of strong continuity, rapid response, and complete data preservation, making it possible to more accurately reflect the dynamic changes of pond environments.

At the network and platform layers, the collected data can be transmitted to local gateways, telecom cloud platforms, or dedicated servers through NB-IoT, Wi-Fi, GSM/SMS, LoRaWAN, and other communication methods (Flores-Iwasaki et al., 2025). Subsequently, the data are stored and managed in IoT cloud services such as ThingSpeak, AWS, and Firebase, or in dedicated data platforms, and are visualized through web dashboards, computer terminals, or mobile applications, thus enabling remote and real-time pond supervision (Lin et al., 2021). Aquaculture operators can use mobile phones, computers, and other terminals to view trends in water quality indicators, equipment operating status, and abnormal alarm information at any time. When the system detects conditions such as excessively low dissolved oxygen, large pH fluctuations, increased ammonia nitrogen concentration, or abnormal water level, it can issue early-warning prompts in a timely manner, helping operators take measures such as aeration, water exchange, water conditioning, or reduced feeding as early as possible.

In more complete digital monitoring systems, data analysis and equipment control can form a linkage mechanism. Control logic is usually implemented through threshold rules, fuzzy logic, or machine learning models, which compare real-time data with ecological setpoints and trigger actuators such as aerators, water pumps, automatic feeders, or dosing systems to correct environmental deviations (Chen et al., 2022). For example, when dissolved oxygen falls below the preset threshold, the system can automatically start aeration equipment; when pH is unstable, the system can prompt or execute regulation measures; when monitoring parameters exceed the limit, relay-controlled water pumps can be used for water exchange (Gleiser and Moro, 2023). More advanced systems can also integrate large amounts of historical data and intelligent algorithms to predict water quality dynamics and

fish survival rates, thereby supporting proactive intervention. Fuzzy logic-based systems can integrate multiple parameters such as temperature, pH, dissolved oxygen, salinity, and weather, and send control instructions through MQTT to maintain optimal environmental conditions with reduced manual intervention (Nagothu et al., 2024). Through this “perception-transmission-analysis-early warning-regulation” operating mode, digital monitoring can shift pond management from passive response to proactive prevention, providing technical support for the precision, intelligence, and efficiency of ecological pond aquaculture.

3 Application Contents of Digital Monitoring in Ecological Pond Aquaculture

3.1 Real-time monitoring of water quality and environmental conditions

The water quality environment is a core factor affecting the effectiveness of ecological pond aquaculture. Changes in indicators such as water temperature, dissolved oxygen, pH, ammonia nitrogen, nitrite, turbidity, and electrical conductivity are directly related to the feeding, growth, disease resistance, and survival rate of cultured organisms. In ecological pond aquaculture, maintaining a stable and suitable water environment is the foundation for achieving the coordinated improvement of production benefits and ecological benefits. Traditional pond aquaculture mainly relies on manual sampling and empirical observation to judge water quality conditions. The monitoring frequency is limited and is easily affected by time, weather, and personnel experience, making it difficult to detect continuous changes in the water environment in a timely manner. By deploying multi-parameter sensors for temperature, pH, dissolved oxygen, turbidity, and electrical conductivity in ponds, and by adding indicators such as ammonia nitrogen and oxidation-reduction potential in some scenarios, digital monitoring systems can continuously transmit data to cloud platforms or local servers through wireless networks, thereby realizing real-time collection, dynamic recording, and remote viewing of water quality and environmental conditions (Figure 1) (Hete et al., 2024).

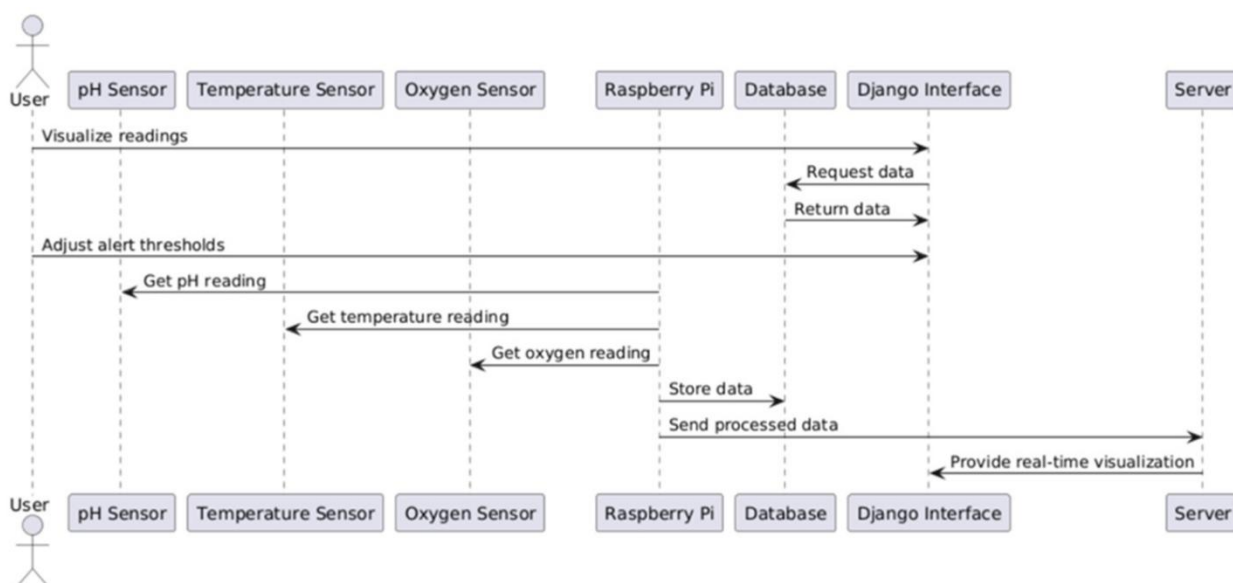


Figure 1 Architectural diagram of IoT system for water quality monitoring and real-time visualization (Adopted from Hete et al., 2024)

In practical applications, real-time monitoring of water quality and environmental conditions can not only reflect the water quality status at a certain point in time, but also form time series and variation curves through continuous data, helping aquaculture operators analyze patterns of water quality fluctuation. Relevant studies have shown that digital monitoring systems can replace traditional low-frequency manual sampling with high-frequency or continuous data collection, and present water quality changes to operators in a more intuitive way through visual dashboards and mobile interfaces (Shete et al., 2024). For example, dissolved oxygen is usually lower in the early morning and increases during the day with enhanced photosynthesis; ammonia nitrogen accumulation and nitrite elevation are more likely to occur in pond water during high-temperature seasons; and

continuous rainy weather may lead to insufficient dissolved oxygen and changes in algal communities. Through the visualization of these data on digital platforms, operators can track daily and seasonal dynamics of water quality, promptly identify abnormal trends that deviate from ecological thresholds, and take measures such as aeration, water exchange, water conditioning, sediment improvement, or reduced feeding in advance, thereby reducing aquaculture risks caused by water quality deterioration.

In addition, real-time monitoring of water quality and environmental conditions also provides basic data support for refined management of ecological ponds. Ecological pond aquaculture emphasizes water ecological balance and environmental friendliness, while relying solely on manual experience makes it difficult to comprehensively judge the complex material cycling and ecological changes within ponds. IoT-machine learning platforms can further use sensor data streams to predict anomalies or outliers in key parameters, enabling managers to intervene rapidly before water quality significantly deteriorates (Forhad et al., 2024). In actual pond applications, integrated monitoring and prediction systems have been used to reduce aquaculture mortality, maintain relatively high survival rates, and support stable production under high-temperature stress (Flores-Iwasaki et al., 2025). For rural ponds with limited resources, the application of low-power wide-area communication technologies such as NB-IoT and LoRaWAN, together with low-cost microcontrollers, also enables continuous monitoring to be extended to remote ecological ponds at relatively acceptable costs (Puangsuwan et al., 2025). Therefore, real-time environmental perception has become an important foundation for refined ecological regulation, risk prevention, and sustainable operation of ecological ponds.

3.2 Intelligent Aeration and Feeding Management

Aeration management is a key link in pond aquaculture. Especially under high-density culture, high-temperature seasons, and sudden weather changes, insufficient dissolved oxygen can easily cause fish and shrimp floating head, stress responses, or even death. Traditional aeration methods usually rely on manual pond inspection to determine whether to turn on aerators, which may lead to delayed activation, unreasonable operating duration, and energy waste. Based on continuous environmental data, digital monitoring can extend from “monitoring water quality” to “automatic regulation” through intelligent control of aerators, water pumps, and other equipment. Many systems connect dissolved oxygen, temperature, and sometimes turbidity or salinity data with automatic aerator or pump control, using threshold logic, fuzzy control, or reinforcement learning to keep dissolved oxygen and other water quality indicators within suitable ecological ranges (Katta et al., 2025; Puangsuwan et al., 2025; Tsai et al., 2022). When dissolved oxygen in the pond falls below the preset threshold, the system can automatically start the aerator; when dissolved oxygen returns to a reasonable range, it can automatically shut down the equipment, thereby improving emergency response speed, reducing human judgment errors, and lowering power consumption caused by ineffective aeration.

Intelligent aeration technology is developing from simple threshold control toward multi-parameter integrated control. Fuzzy logic-based pond management platforms can integrate multiple input parameters, such as temperature, pH, dissolved oxygen, weather, and salinity, and autonomously regulate aerators and water pumps according to dynamic changes. In pond tests, such systems have maintained desirable dissolved oxygen and salinity levels, showing relatively high control accuracy and stability. Some studies have also designed smart aquaculture systems with automatic aeration and water quality monitoring functions. When dissolved oxygen falls below the set limit, the system can automatically activate aeration devices, significantly improving shrimp survival compared with traditional ponds (Tsai et al., 2022). Therefore, intelligent aeration can not only address hypoxia risks, but also improve energy utilization efficiency and management precision by reducing ineffective operation.

Feeding management is also an important factor affecting aquaculture benefits and the water environment. Insufficient feeding affects the growth of cultured organisms, whereas excessive feeding causes feed waste and the accumulation of residual feed and excreta in ponds, leading to increased ammonia nitrogen, elevated nitrite, and sediment deterioration. IoT-based aquaculture systems can control automatic feeders through scheduled or

intelligent strategies while monitoring water quality, thereby avoiding overfeeding and pond environmental deterioration (Katta et al., 2025; Puangsuwan et al., 2025). Digital monitoring technology can optimize feeding amount, feeding time, and feeding frequency by combining water temperature, dissolved oxygen, weather conditions, growth stage of cultured organisms, and feeding behavior. For example, feeding can be appropriately increased when water temperature is suitable, dissolved oxygen is sufficient, and feeding activity is high; under low oxygen, cooling, heavy rainfall, or abnormal water quality conditions, feeding should be reduced or suspended to avoid increasing the environmental burden of the pond. Deep reinforcement learning has been applied to the joint optimization of feeding rates and water quality in recirculating aquaculture systems, helping reduce feed consumption, improve system stability, and generate economic benefits (Elmessery et al., 2025). Edge artificial intelligence and deep Q-network-based frameworks can further coordinate feeding, aeration, and water exchange, improving feed conversion efficiency and reducing energy consumption (Katta et al., 2025). In ecological pond scenarios, the integration of intelligent aeration and feeding management helps match energy input and feed input with ecosystem carrying capacity, thereby promoting pond aquaculture toward energy-saving, efficient, and environmentally friendly development.

3.3 Disease Early Warning and Production Process Traceability

Disease prevention and control are key and difficult aspects of ecological pond aquaculture management. Pond aquaculture diseases are often closely associated with water quality deterioration, excessive stocking density, improper feeding, abrupt temperature changes, and stress responses of cultured organisms. Traditional disease prevention and control mainly rely on operators observing the activity, feeding, and mortality of fish and shrimp, and treatment measures are often taken only after disease has already occurred, which can easily miss the optimal prevention and control window. Through continuous collection of water quality, meteorological, equipment operation, and production management data, digital monitoring technology can identify environmental abnormal signals before disease occurrence and provide a basis for early disease warning. Relevant studies have shown that by combining continuous water quality data, such as temperature, dissolved oxygen, pH, salinity, and nutrients, with disease surveillance records, machine learning models can identify environmental risk patterns and predict outbreaks of specific parasitic or other diseases (Islam et al., 2024; Xie et al., 2025; Rohini et al., 2026).

In practical applications, when the system detects conditions such as continuously low dissolved oxygen, abnormal increases in ammonia nitrogen or nitrite, large pH fluctuations, or sharp changes in water temperature, it can promptly send early-warning alerts to aquaculture operators. Operators can then inspect pond conditions according to the alarm information and take measures such as improving water quality, adjusting feeding, strengthening aeration, applying microbial preparations, or conducting pathogen detection, thereby reducing the risk of disease outbreaks. For example, Xie et al. (2025) integrated multi-year disease outbreak data with high-resolution environmental predictors to construct an early-warning system for cryptocaryoniasis in marine fish, and provided weekly updated spatially resolved prediction information to farmers through a web platform. More general smart aquaculture systems can also apply machine learning or deep learning to image and sensor data to identify abnormal fish behavior or lesion characteristics, providing early warnings for disease intervention and reducing mortality and economic losses (Islam et al., 2024; Rohini et al., 2026). Some digital systems can further combine video monitoring and feeding behavior analysis to assist in judging whether cultured organisms show abnormal activity, reduced feeding, or floating head aggregation, thereby further improving the accuracy of disease risk identification.

Digital monitoring can also be used for production process traceability management. By using data platforms to record seedling sources, stocking time, feed input, medication use, water quality changes, equipment operation, disease treatment, and product harvest information, relatively complete aquaculture records can be formed. This not only helps operators summarize production experience and analyze the causes of problems, but also helps standardize aquaculture operations and improve the quality and safety management of aquatic products. AI-IoT-blockchain schemes can record water quality, feeding, growth, and disease-related information in tamper-resistant ledgers, enabling end-to-end traceability from seedling stocking to harvest, and supporting the

verification of product safety and environmental compliance (Premkkumar et al., 2023). Blockchain-based smart contracts can also support secure sharing of health and management data among stakeholders in disease early-warning networks. Integrated AI-IoT platforms can combine real-time sensing, disease classification, and time series prediction, enabling operators to receive automated recommendations and alerts through web or mobile terminals, while historical logs support auditing and optimization of management strategies (Katta et al., 2025; Rohini et al., 2026). For ecological pond aquaculture, production process traceability can enhance product credibility and market competitiveness, and also provide data support for regulatory authorities to carry out quality and safety supervision, tailwater discharge management, and green aquaculture evaluation.

4 Analysis of the Application Effects of Digital Monitoring in Ecological Pond Aquaculture

4.1 Improving Water Quality Regulation Efficiency

The primary application effect of digital monitoring in ecological pond aquaculture is reflected in the improvement of water quality regulation efficiency. Pond water environments have obvious dynamic characteristics, and indicators such as dissolved oxygen, water temperature, pH, ammonia nitrogen, nitrite, and turbidity are affected by multiple factors, including weather changes, feeding intensity, stocking density, algal growth, and sediment conditions. Traditional management mainly relies on manual pond inspection and regular testing, which often only capture water quality conditions at a specific point in time and cannot promptly reflect changing trends in the water environment. Through the coordinated application of multi-parameter sensors, microcontrollers, and wireless communication technologies, digital monitoring systems can continuously collect and display key indicators such as temperature, pH, dissolved oxygen, and turbidity in real time, thereby providing a data basis for rapid corrective actions (Chen et al., 2022). Compared with traditional manual testing, calibrated low-cost sensors can significantly improve the reliability of real-time monitoring; in some systems, after linear regression correction, the accuracy can reach 76%-97%, with relative errors below 4% (Jais et al., 2024).

In specific management processes, digital monitoring can transform water quality data into intuitive trend charts and alarm information, helping aquaculture operators judge the direction and degree of pond environmental changes. For example, when dissolved oxygen continues to decline, the system can remind operators to start aeration equipment in time; when ammonia nitrogen or nitrite increases, operators can take measures such as water exchange, sediment improvement, feeding reduction, or the application of microbial preparations according to actual conditions; when pH fluctuates greatly, operators can also make comprehensive judgments by considering algal community changes and weather conditions. Monitoring architectures based on fuzzy logic and artificial intelligence can further integrate multi-source data and automatically control aerators, water pumps, and other equipment to maintain suitable dissolved oxygen and salinity levels during continuous operation and rapidly correct water quality deviations. As a result, water quality regulation no longer relies entirely on empirical judgment, but is instead based on continuous data, real-time feedback, and equipment linkage, making management measures more targeted and timely.

The improvement of water quality regulation efficiency is also reflected in enhanced preventive management capacity. Digital monitoring can not only detect existing abnormalities, but also identify potential risks through the accumulation of continuous data. For example, low dissolved oxygen in the early morning during high-temperature seasons, weakened photosynthesis in rainy weather, and increased water load after excessive feeding can all be reflected in data changes in advance. Predictive and intelligent control further enhances this preventive capacity. IoT-machine learning-quantum optimization frameworks can predict water quality dynamics with relatively high accuracy and support a large number of targeted interventions, keeping fish survival rates above 90% in tropical ponds (Huang and Khabusi, 2025). Relevant reviews also show that continuous monitoring combined with automatic aeration, dosing, or water exchange can rapidly detect and mitigate abnormalities in dissolved oxygen, pH, and total ammonia nitrogen, reduce environmental risks, and stabilize aquaculture conditions (Figure 2) (Flores-Iwasaki et al., 2025). Therefore, digital monitoring helps ecological pond aquaculture shift from post-event treatment to pre-event prevention, thereby improving the stability of the entire aquaculture system.

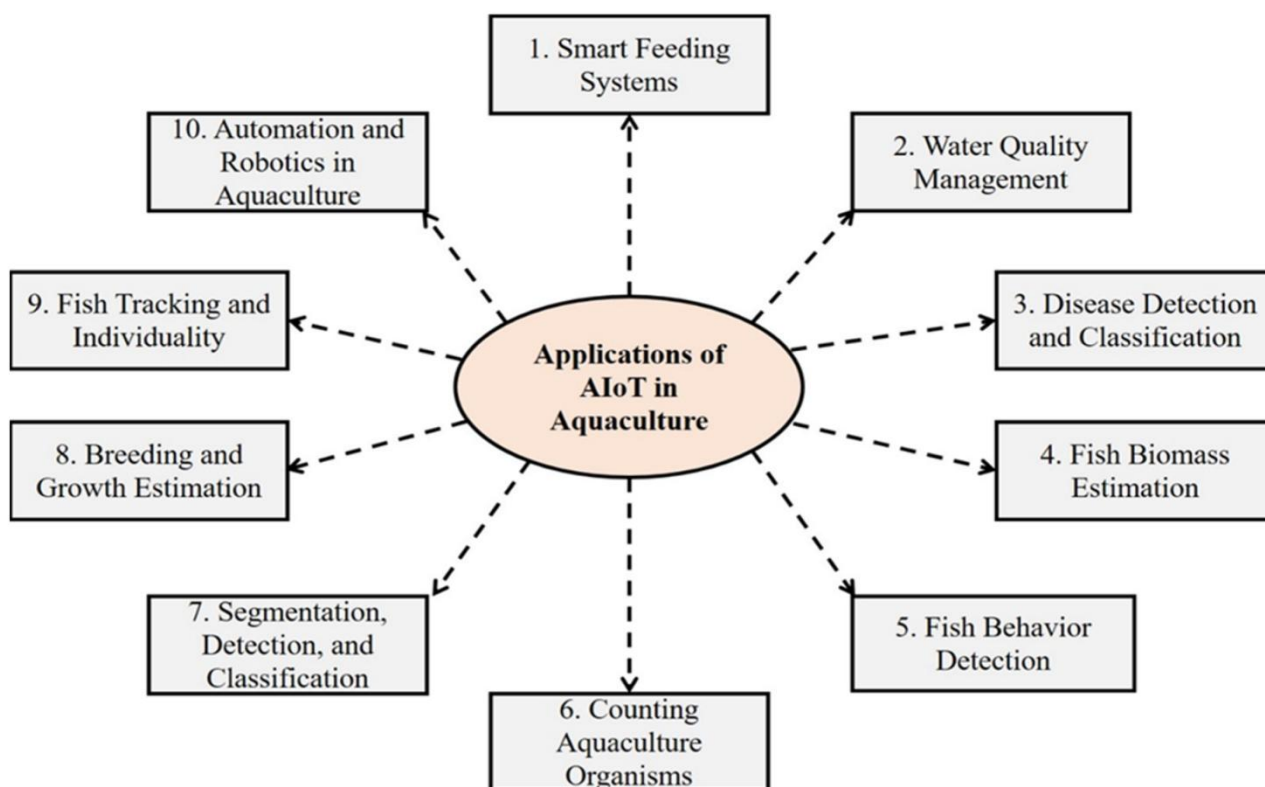


Figure 2 Applications of AIoT in aquaculture (Adopted from Huang and Khabusi, 2025)

4.2 Reducing Aquaculture Management Costs

Digital monitoring can effectively reduce labor management costs in ecological pond aquaculture. Traditional pond aquaculture requires frequent pond inspections by personnel, especially during high-risk periods such as nighttime, early morning, high temperatures, heavy rainfall, and muggy weather, when manual observation is needed to judge whether hypoxia, floating head, or abnormal water color has occurred. This approach not only involves high labor intensity, but is also constrained by personnel experience and inspection frequency. By replacing frequent manual sampling with automated and networked sensing, digital monitoring can directly reduce labor and routine monitoring costs. Compact IoT systems and smart printed circuit boards can achieve accurate multi-parameter monitoring with less manual intervention and lower maintenance costs, while also preventing disease and mortality through data-driven decision-making. Automated equipment such as mobile robots and robotic arms can further automate sensor deployment and pH measurement, support 24-hour operation, and significantly reduce personnel time, material consumption, and data collection errors (Chen et al., 2022; Hemal et al., 2024).

In terms of equipment operation costs, digital monitoring can reduce energy waste through precise control. Taking aeration equipment as an example, in traditional management, aerators are often kept running for long periods due to concerns about hypoxia, which can increase electricity consumption; alternatively, delayed activation may create aquaculture risks. Digital systems can automatically control the start and stop of aeration equipment according to changes in dissolved oxygen, making equipment operation more precise. Similarly, intelligent feeding systems can adjust feeding amounts according to water temperature, dissolved oxygen, feeding status, and growth stage, thereby reducing waste caused by excessive feed input. Studies on precision aquaculture and smart aquaculture indicate that Industry 4.0 and AIoT systems, especially intelligent aeration and feeding technologies, can reduce feed waste by about 30%, reduce energy consumption by up to 35%, and improve feed conversion efficiency by about 22% (Yavuzcan and Mansour, 2026). Since feed and electricity are important cost sources in pond aquaculture, digital monitoring has a direct role in reducing overall production costs.

In addition, digital monitoring can also reduce hidden costs caused by management errors. Water quality deterioration, hypoxia-induced floating head, disease outbreaks, and improper feeding can all lead to growth retardation, increased mortality, greater medication use, and declining product quality, and these losses are often higher than routine equipment investment costs. Automated monitoring and corrective systems can reduce severe losses, improve environmental management, lower production costs, and relieve pressure on aquaculture operators (Kannan et al., 2024). At the farm or industry level, precision aquaculture and AI-based platforms have demonstrated effects in reducing labor and energy costs, with investment payback periods usually ranging from 1 to 3 years, especially for larger-scale aquaculture operators (Dhamdhare et al., 2025). Although digital monitoring systems require certain equipment investment and maintenance costs at the initial construction stage, in the long run they have strong comprehensive benefits in reducing labor input, saving energy, reducing feed waste, and preventing aquaculture risks.

4.3 Enhancing Aquaculture Yield and Product Quality

The contribution of digital monitoring to aquaculture yield improvement is mainly reflected in creating a more stable and suitable growth environment for cultured organisms. Aquatic animals are highly sensitive to changes in water quality. Insufficient dissolved oxygen, ammonia nitrogen accumulation, abnormal pH, and sharp water temperature fluctuations can all affect their feeding, growth, and immune function. Through digital monitoring systems, aquaculture operators can promptly understand pond environmental conditions and conduct precise regulation according to data changes, thereby reducing environmental stress on cultured organisms. Previous studies have shown that environmental stability achieved through digital monitoring can be translated into better growth performance, lower mortality, and higher product quality. Automated water quality monitoring and intervention systems in intensive aquaculture have been shown to reduce fish mortality, improve management efficiency, and clearly enhance product quality (Narsale et al., 2024). IoT-based monitoring combined with automatic correction can keep key parameters within optimal ranges and is associated with better fish health and higher survival rates; in relevant pond studies, timely interventions enabled fish survival rates to remain above 90% under tropical conditions.

In terms of product quality, digital monitoring helps promote standardized and safe aquaculture processes. By recording data on water quality, feeding, medication use, equipment operation, and environmental changes, aquaculture operators can arrange production management more scientifically and reduce problems such as blind medication and excessive feeding. A good water environment can reduce the probability of disease occurrence and decrease the frequency of drug use, which is conducive to improving the safety and quality stability of aquatic products. Systematic reviews show that IoT-based water quality monitoring can improve growth rates, reduce aquaculture mortality, and enhance the prediction and management of harmful total ammonia nitrogen levels, thereby supporting more robust production (Flores-Iwasaki et al., 2025). At the same time, ecological pond aquaculture emphasizes green production and environmental friendliness, and digital monitoring provides more refined data support, making products more consistent with consumer demand for green, healthy, and traceable aquatic products.

From a broader perspective, precision aquaculture and AIoT frameworks generally show positive effects on yield and product value. Reviews and case studies indicate that when smart monitoring is combined with automatic feeding and aeration, productivity can increase by 15%-50%, feed efficiency can improve by about 30%, and yield can increase by up to 30% (Katta et al., 2025). AI systems in commercial settings have also recorded 15%-30% reductions in feed costs, up to 20% reductions in disease-related mortality, and improved compliance with environmental and quality standards, thereby enhancing the market competitiveness of aquaculture products and consumer trust (Liu et al., 2025). Overall, by improving the aquaculture environment, optimizing production operations, and strengthening process management, digital monitoring not only helps increase the yield of ecological pond aquaculture, but also contributes to the production of more uniform, safer, and traceable aquatic products.

5 Problems in the Application of Digital Monitoring

5.1 High equipment investment and maintenance costs

The promotion and application of digital monitoring systems in ecological pond aquaculture first face the problem of relatively high equipment investment costs. A complete digital monitoring system usually includes multiple components, such as water quality sensors, data acquisition terminals, communication modules, power supply systems, monitoring platforms, intelligent aeration equipment, intelligent feeding equipment, and mobile management terminals. Although many studies emphasize that IoT-based water quality monitoring systems can be designed as “low-cost” solutions, for small- and medium-sized aquaculture farms, the initial investment in sensors, controllers, communication modules, and supporting infrastructure remains a major burden. Relevant studies have shown that even cost-optimized systems for recirculating aquaculture or pond scenarios usually require hardware budgets of tens to hundreds of dollars per unit, while commercial integrated systems may cost thousands of euros and involve high operation and maintenance expenses (Figure 3) (Malandrakis, 2025). Reviews on smart sensors and AIoT solutions in agriculture and aquaculture have also pointed out that high infrastructure and equipment costs are important barriers to large-scale deployment, especially among smallholders and rural producers (Tina et al., 2025).

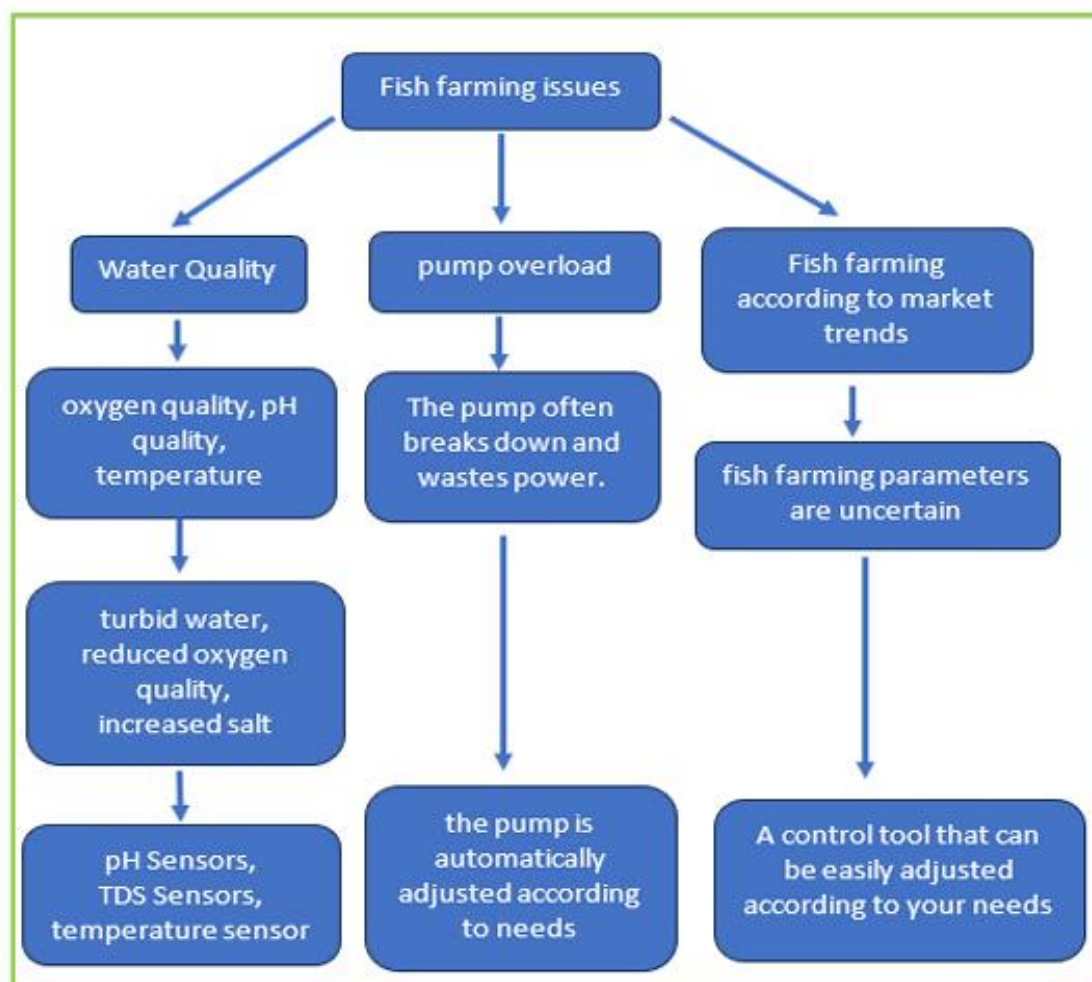


Figure 3 Illustration of Problems Commonly Found in Traditional Aquaculture Systems (Adopted from Subowo and Pradita, 2025)

In addition to the initial purchase cost, equipment operation and maintenance costs should not be ignored. Water quality sensors are exposed to pond water environments for long periods and are easily affected by sediment adhesion, algal contamination, biofilm coverage, and equipment aging. Therefore, they require regular cleaning, calibration, and replacement of components. If maintenance is not conducted properly, data accuracy may be affected, equipment service life may be shortened, and subsequent repair costs may increase. Meanwhile, the

operation of digital platforms, network communication, data storage, software upgrades, and remote services also require continuous investment. IoT-related reviews emphasize that connectivity in remote ponds often relies on low-power wide-area networks, satellite networks, or mobile networks, whose deployment and service fees may further increase costs; at the same time, ensuring stable power supply for devices may require additional energy systems. AIoT assessments further indicate that data processing infrastructure, as well as energy-intensive computing and communication, may also bring certain environmental and economic burdens (Tina et al., 2025).

In addition, the cost-effectiveness of digital monitoring equipment varies across different aquaculture scenarios. High-density aquaculture, high-value aquatic product farming, and large-scale ecological aquaculture have stronger demands for environmental monitoring, risk warning, and process traceability, so digital investment is more likely to be transformed into economic returns. However, in low-density, extensive, or seasonal aquaculture scenarios, equipment utilization may be insufficient and the investment payback period may be relatively long. For ecological pond aquaculture, if profit margins are limited and ponds are numerous and spatially dispersed, the accumulated costs of sensors, networks, power supply, and maintenance services may slow down promotion and application even when the technical benefits are recognized. Therefore, the promotion of digital monitoring systems should not simply pursue complete equipment configuration, but should select appropriate technical models and equipment combinations according to aquaculture scale, species value, management needs, and economic affordability.

5.2 Insufficient data accuracy and system stability

The application effect of digital monitoring largely depends on data accuracy, continuity, and system stability. However, in ecological pond aquaculture environments, monitoring equipment faces complex operating conditions. Factors such as turbid water, algal proliferation, sediment disturbance, temperature changes, biofouling, and long-term immersion may all affect sensor detection results. Many studies have shown that although low-cost sensors help reduce the threshold for application, they are also susceptible to drift, biofouling, and environmental interference. For example, if monitoring probes for indicators such as dissolved oxygen, pH, and ammonia nitrogen are not cleaned and calibrated in time, data drift or errors may occur, resulting in inaccurate system alarms. Analyses of smart sensor performance in aquaculture have indicated that electrochemical dissolved oxygen and nutrient sensors may show measurable deviations over time due to biofilm accumulation and electrode aging, thus requiring frequent recalibration to avoid delayed or incorrect management responses (Zamnuri et al., 2024).

Insufficient system stability is also a practical issue in the promotion of digital monitoring. Pond aquaculture is mostly located in rural or suburban areas, where network signals may be unstable in some regions, easily causing data transmission delays, platform disconnection, or failure of remote control. Under special weather conditions such as thunderstorms, high temperatures, and humidity, outdoor equipment may also experience line aging, abnormal power supply, terminal damage, and other problems. If the system cannot maintain stable operation, the continuity and early-warning function of digital monitoring will be affected. To improve data integrity, many system studies have adopted pre- and post-calibration procedures, outlier rejection algorithms, cross-validation with professional instruments, or regression-based correction of low-cost sensor data (Lin et al., 2021). However, even with these measures, IoT and AIoT applications in aquaculture still face problems such as data loss caused by equipment or network failures, unstable connectivity, and uncertainty in predictive models, all of which may affect the reliability of real-time decision-making (Tina et al., 2025).

At the same time, some digital monitoring systems still have insufficient data analysis capabilities. At present, some systems mainly remain at the stage of data collection, indicator display, and simple threshold alarms, and their ability to make differentiated judgments under different cultured species, seasons, and ecological pond conditions is limited. For example, the same dissolved oxygen level may represent different degrees of risk under different water temperatures, stocking densities, and cultured species. If the system only issues alarms based on fixed thresholds, false alarms or missed alarms may occur. In ecological pond applications, management decisions

such as aeration, feeding, and water exchange depend on continuous and reliable data. Therefore, insufficient data accuracy and system stability increase operational risks and place higher requirements on technical maintenance, on-site calibration, and model optimization. In the future, digital monitoring systems need to further improve sensor durability, data correction capability, communication stability, and model adaptability, so that monitoring results can better meet actual production needs.

5.3 Limited digital application capacity of aquaculture operators

The effective application of digital monitoring systems depends not only on the equipment itself, but also on the digital application capacity of aquaculture operators. At present, some operators have long relied on experience-based pond management and lack sufficient understanding of water quality indicator variation patterns, data platform operation, abnormal alarm interpretation, and equipment linkage control. Digital monitoring systems assume that pond operators possess a certain level of digital literacy and can install, understand, and act upon complex data streams. However, systematic reviews on agricultural digital literacy and technology adoption have shown that limited digital skills, low formal education levels, and weak digital infrastructure can create a “capacity gap” that restricts the effective use of precision and intelligent technologies, causing many technologies to remain at the pilot or demonstration stage (Arangurí et al., 2025; Liu et al., 2025). Even after installing digital monitoring equipment, some operators may only use it as a simple data display tool and fail to fully use the data for trend analysis and management decision-making. This phenomenon of “emphasizing equipment while neglecting application” weakens the practical role of digital monitoring in ecological pond aquaculture.

Some aquaculture operators’ trust in and acceptance of digital technologies also need to be improved. Some operators are accustomed to making empirical judgments based on water color, odor, fish and shrimp activity, and weather changes. When monitoring data are inconsistent with their own empirical judgment, they may be unwilling to adjust management measures according to system prompts. Some operators are also concerned that the equipment is complicated to operate, difficult to maintain, or hard to interpret, thereby affecting their willingness to continue using it. Empirical studies on farmers’ adoption of green or low-carbon technologies have found that higher digital literacy significantly increases technology adoption rates, while deficiencies in information acquisition, problem solving, and security literacy reduce their willingness and ability to use data-driven tools (Liu et al., 2025). Reviews on IoT and AIoT in aquaculture also point out that perception-related barriers are important factors limiting technology promotion, including operators’ insufficient awareness of technical benefits, skepticism about system reliability, and lack of technical expertise required for system operation and maintenance (Tina et al., 2025).

In addition, grassroots technical service systems still cannot fully meet the needs of digital aquaculture promotion. Digital monitoring involves knowledge in aquaculture, information technology, equipment maintenance, and data analysis. It is often difficult for operators to achieve ideal application results through individual learning alone. Case studies of digital training programs have shown that targeted practical training and follow-up support can improve farmers’ confidence, digital literacy, and technology-use behavior, but device limitations, network problems, and perceived technological complexity may still hinder widespread application. In ecological pond aquaculture, operators need to comprehensively consider environmental, production, and economic factors. If their digital application capacity is insufficient, monitoring platforms may be underused, excessive dependence on external technicians may occur, and collected data may be difficult to transform into timely ecological management actions. Therefore, improving the digital application capacity of aquaculture operators requires the joint participation of governments, research institutions, enterprises, and extension departments. Demonstration base construction, technical training, on-site guidance, and remote services should be used to enhance the practical application level of digital monitoring technologies.

6 Optimization Strategies for Digital Monitoring in Ecological Pond Aquaculture

6.1 Improving the configuration of digital monitoring equipment

To promote the application of digital monitoring in ecological pond aquaculture, sensors, controllers,

communication modules, and intelligent actuators should first be scientifically configured according to aquaculture scale, cultured species, pond conditions, and management objectives. Different ponds vary in area, water depth, stocking density, water source conditions, and environmental risks, so the required monitoring indicators and the number of devices are not exactly the same. For ordinary ecological ponds, priority should be given to basic monitoring equipment for water temperature, dissolved oxygen, and pH. For high-density aquaculture ponds or ponds for high-value aquatic products, ammonia nitrogen, nitrite, turbidity, meteorological monitoring, and video monitoring equipment should be further added to improve risk identification capacity. Previous studies have shown that compact integrated printed circuit boards and microcontroller-based systems, such as Arduino, ESP32, and STM32, can stably collect key parameters such as temperature, pH, dissolved oxygen, and turbidity in real time with relatively low maintenance and hardware costs, making them suitable for continuous monitoring in pond aquaculture scenarios (Abdikadir et al., 2024; Olanubi et al., 2024). Meanwhile, systematic calibration and linear regression comparison with professional instruments can further improve the accuracy of low-cost sensors, increasing their accuracy to 76%-97% and reducing relative errors to below 4%, thereby enhancing their applicability in continuous monitoring of ecological ponds (Obiero et al., 2019).

Equipment configuration should also emphasize practicality, stability, compatibility, and low energy consumption. Most ecological ponds are exposed outdoor environments, where equipment is affected for long periods by water immersion, sunlight, rainfall, temperature and humidity changes, and biofouling. Therefore, sensors and control terminals with strong waterproof, anti-corrosion, and anti-interference capabilities should be selected. At the same time, monitoring equipment should be easy to install, clean, calibrate, and replace, thereby reducing the difficulty of daily maintenance for aquaculture operators. For ponds that already have aerators, feeders, water pumps, and other equipment, digital transformation can be achieved by adding intelligent control modules rather than completely replacing existing equipment, thereby improving equipment utilization and renovation cost-effectiveness. In terms of communication methods, NB-IoT, LoRa, and Wi-Fi modules can realize long-distance transmission or cloud connection with relatively low power consumption, allowing remote ponds to maintain continuous monitoring (Malandrakis, 2025). In areas with weak infrastructure or limited network bandwidth, hybrid architectures that support both local processing and cloud analysis can also be adopted to ensure stable system operation under rural low-bandwidth conditions.

In addition, a daily maintenance system and redundancy guarantee mechanism for digital monitoring equipment should be established. During sensor use, problems such as data drift, probe contamination, and line failures may occur. Without regular inspection, the reliability of monitoring results will be directly affected. Therefore, aquaculture operators should regularly conduct probe cleaning, data calibration, line inspection, outlier screening, and software upgrading according to equipment operation requirements, and establish maintenance records. Multi-sensor nodes can be combined with outlier rejection algorithms, and redundant monitoring can be set for key parameters such as dissolved oxygen and pH to improve data integrity and system fault tolerance (Flores-Iwasaki et al., 2025). For large-scale aquaculture bases, specialized technical personnel can be assigned to equipment operation and maintenance. For small- and medium-sized operators, cooperatives, technical service companies, or grassroots extension institutions can provide centralized maintenance services to ensure the long-term stable operation of digital monitoring systems.

6.2 Establishing scientific data management and early-warning mechanisms

The core value of digital monitoring lies not only in data collection, but also in scientific data management and effective utilization. Digital monitoring of ecological ponds generates large amounts of time-series data, including water quality indicators, equipment operation, feeding records, medication use, meteorological changes, alarm information, and aquaculture results. Without a standardized data management mechanism, problems such as data dispersion, duplicate records, inconsistent formats, and “collection without analysis” may easily occur. Therefore, unified mechanisms for data collection, classified storage, dynamic analysis, and secure management should be established, together with platform interfaces that support intuitive charts, data queries, historical curves, and report export, so that monitoring data can truly serve aquaculture decision-making. Many systems have uploaded

multi-parameter data to IoT cloud platforms, such as ThingsBoard, ThingSpeak, Virtuino dashboards, QuickSight, and Grafana, for real-time visualization and historical analysis. These systems also integrate alarm modules that notify operators via SMS, applications, or push services when monitoring values exceed thresholds. Scientific data management should include unified data formats, secure storage, and long-term analysis interfaces to reduce the risk of data loss and facilitate long-term evaluation of ecological pond performance (Wei et al., 2023).

The construction of early-warning mechanisms is an important link in improving the application effects of digital monitoring. Risks in ecological pond aquaculture are often both gradual and sudden, and a single fixed threshold is difficult to adapt to complex production scenarios. Therefore, a more flexible early-warning indicator system should be established by considering cultured species, growth stage, seasonal characteristics, weather changes, and historical data. For example, dissolved oxygen warning should comprehensively consider water temperature, time period, stocking density, and weather conditions; warnings for ammonia nitrogen and nitrite should be judged in combination with feeding intensity, sediment conditions, and water exchange conditions. By constructing a graded early-warning mechanism, risks can be divided into different levels, such as general reminder, key attention, and emergency treatment, thereby improving the practicality of warning information. Previous studies have shown that remote monitoring devices equipped with upper and lower thresholds, buzzer or LED alarms, and mobile notifications can respond quickly after dangerous changes occur and constitute an important component of early-warning systems in pond and marine aquaculture (Ntiri et al., 2022).

On this basis, early-warning mechanisms should also be upgraded from simple threshold alarms to intelligent prediction and anomaly detection. IoT-machine learning-quantum approximate optimization algorithm frameworks and long short-term memory (LSTM)-based prediction systems can use historical water quality data to predict future changes in dissolved oxygen, pH, or turbidity, and support timely corrective interventions, thereby improving pond aquaculture survival rates and management stability (Wei et al., 2023). Systematic reviews indicate that integrating artificial intelligence algorithms such as linear regression, decision trees, and random forests into the data processing layer helps predict outliers and avoid deviations from optimal parameter ranges (Pramana et al., 2021). In data management and early-warning applications, monitoring platforms should also be linked with intelligent control equipment. For issues with clear treatment measures, such as low dissolved oxygen, abnormal water levels, or equipment operation failures, automatic control programs can be set to realize automatic start and stop of aerators, water pumps, valves, and other equipment. For disease risks or water quality deterioration trends that require comprehensive judgment, platforms should push warning information to guide operators in conducting on-site inspections and manual interventions in time. Through the operating mechanism of “data collection-trend analysis-risk warning-equipment linkage-manual decision-making,” the response speed and decision quality of ecological pond aquaculture management can be improved.

6.3 Strengthening technical training and extension services

Whether digital monitoring technology can truly function depends on whether aquaculture operators have the corresponding application capacity and management awareness. Even the most complete digital system cannot fully function without users who understand, trust, and can maintain it. Therefore, technical training should be strengthened for aquaculture farmers, cooperatives, and aquaculture enterprises to help them understand the meanings of major water quality indicators, their variation patterns, and their impacts on aquaculture production. Training should not stop at equipment operation, but should also include data viewing, trend judgment, alarm handling, equipment maintenance, platform use, and production decision-making, so that operators can transform digital monitoring results into specific management measures. Aquaculture survey and extension studies show that education level, ease of understanding technologies, ease of handling technologies, and participation in extension training are important positive predictors of technology adoption and livelihood improvement (Kwikiriza et al., 2026).

In terms of promotion methods, demonstration base construction should be used to improve aquaculture operators' awareness of and trust in digital monitoring technology. Representative ecological pond aquaculture

areas can be selected to build a number of digital monitoring application demonstration sites, showing their practical effects in water quality regulation, energy saving and consumption reduction, precision feeding, disease early warning, and quality traceability. Through on-site observation, technical explanation, benefit comparison, and experience exchange, operators' willingness to apply digital monitoring can be strengthened. At the same time, research institutions, equipment enterprises, and grassroots aquaculture technology extension departments should be encouraged to participate collaboratively, providing aquaculture operators with whole-process services from equipment selection and installation commissioning to later-stage maintenance. Studies have shown that ICT-based extension through mobile phones, social media, television, and radio can improve the adoption of good management practices, productivity, and income more effectively than traditional extension services alone, especially when combined with face-to-face extension. Broader evidence from agriculture and fisheries also shows that digital platforms, online training, and participatory learning, when combined with community action and peer networks, can bridge digital literacy gaps and overcome sociocultural barriers (Hidayat et al., 2024; Inutan et al., 2025).

In addition, policy support and service systems for the promotion of digital monitoring should be improved. Relevant government departments can provide equipment purchase subsidies, technical service support, or demonstration project assistance to eligible aquaculture operators in combination with smart agriculture, green aquaculture, and high-quality fishery development projects, thereby lowering application thresholds. For small- and medium-sized operators, models such as unified cooperative construction, regional platform sharing, and third-party entrusted operation and maintenance can be explored to reduce the investment pressure on individual households. Studies on extension systems emphasize that a blended “digital + human” extension approach, competency-based training, and close links among research institutions, extension departments, and farmers are key to sustained technology use (Rowan, 2022). Through localized training materials, multilingual ICT tools, and coordinated advisory services from the public and private sectors, ecological pond aquaculture regions can promote broader and more effective application of digital monitoring and build long-term capacity for data-driven sustainable aquaculture.

7 Conclusions and Prospects

Existing studies show that digital monitoring based on IoT sensors and intelligent algorithms can significantly improve the management performance of pond and tank aquaculture. Real-time sensing of temperature, pH, dissolved oxygen, and turbidity can provide accurate and continuous data. Properly calibrated low-cost systems can achieve an accuracy of 76%-97% with low relative errors, while NB-IoT- or ESP-based platforms demonstrate stable transmission, low maintenance requirements, and effective support for water quality regulation. Integration with machine learning and optimization methods enables high-precision prediction and rapid intervention. Integrated IoT-ML-QAOA systems have implemented thousands of corrective actions in ponds while maintaining fish survival rates above 90%; fuzzy logic control can also maintain dissolved oxygen and salinity within optimal ranges with high reliability. Overall, digital monitoring improves water quality regulation efficiency, reduces disease and mortality, and supports higher yields and sustainable development in aquaculture systems.

Looking ahead, the application of digital monitoring in ecological pond aquaculture is expected to expand from single-pond management to larger-scale, networked, and value-chain-oriented systems. Reviews on CIA (Cloud Computing-Internet of Things-Artificial Intelligence) and Industry 4.0 emphasize that smart sensors, cloud platforms, AI analytics, and even blockchain will increasingly support functions such as traceability, feeding optimization, disease detection, growth prediction, environmental monitoring, and market information, thereby improving productivity and sustainability across the entire aquaculture value chain. Systematic reviews of digital technologies in aquaculture supply chains identify sustainability, circular economy, food safety, and food security as core “driving themes,” indicating that end-to-end digital monitoring and data sharing will become key tools for the development of green, low-carbon, and climate-resilient aquaculture.

Future development should focus on the deeper integration, scalability, and inclusiveness of digital monitoring in ecological ponds. Technically, it is necessary to strengthen the automation of parameter control, improve sensor robustness and maintenance convenience in rural environments, and embed advanced artificial intelligence, including hybrid machine learning-quantum algorithms, into monitoring platforms for early anomaly prediction and climate-adaptive decision-making. At the system level, scholars have called for coordinated “Aquaculture 4.0” and federated data ecosystems that connect farm-level IoT data with regional and global platforms to support environmental and social sustainability, rather than merely improving individual operational efficiency. At the governance and adoption level, future research should address high infrastructure costs, insufficient data quality and interoperability, and the digital capacity gap among smallholders, while promoting multi-stakeholder collaboration so that disruptive technologies such as the Internet of Things, artificial intelligence, blockchain, and robotics can enhance, rather than undermine, the sustainability and equity of aquaculture development.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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