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IoT and artificial intelligence applications in aquaculture: Implications for water quality, fish health, food safety, and human health

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Abstract
Aquaculture is one of the fastest-growing food production sectors worldwide and plays a key role in meeting the increasing global demand for seafood. Water quality is essential for the health, growth, and survival of fish. Conventional methods for monitoring water are excessively time-consuming and cannot provide the real-time information required for good management. A comprehensive review of Internet of Things (IoT) based fishpond systems is given, concentrating on hardware devices, sensor technologies, communication protocols, data management and Artificial Intelligence (AI) / Machine learning (ML) integration. Research papers published from 2015 to 2025, which report on sensor devices or water parameters, including AI-ML techniques, were considered. Information on hardware platform (cameras, acoustic, or other) monitored fish species, examined parameter connectivity , biological impact and key findings was recorded. IoT-based systems can continuously measure parameters such as temperature, pH and dissolved oxygen, and in some cases ammonia and nitrates directly from the source. It is cloud computing and AI/ML compatible for real-time monitoring, predictive analysis and intelligent decision making. System cost, connectivity and scalability vary, from inexpensive solutions for small farmers to alternatives that emphasize automation and high precision. To date, there are still challenges for the monitoring of biological markers, low-power connectivity and predictive capabilities. For smart aquaculture, the application of IoT technologies holds transformational power in that it can improve water quality control, fish well-being and commercial value. Future work should consider the development of integrated and adaptive systems that combine environmental and biological sensing, low-power networks as well as AI/ML support for predictive management in sustainable and profitable aquaculture.

Introduction

It is imperative to provide the increasing demand for seafood in the global arena, including the managed growth of sea animals. The primary causes of this demand include population growth, the exhaustion of wild fish resources, and the shift towards more sustainable and healthy food products [1]. The water quality in the conditions in which fish grow greatly affects the volume and quality of fish produced by the aquaculture process [2]. Nevertheless, climate change and the rising cases of dumping hazardous and solid waste into water bodies are negatively affecting water quality and posing a severe threat to aquatic organisms [3].

Water quality affects the physiological [4], biochemical [5], and behavioral processes [6] of aquatic life, in particular fish, which is a critical factor in defining the overall health of aquatic life [7]. The metabolic rate of fish and the functioning of various internal organs and general physiological stability may also be influenced by differences in the water conditions surrounding them [8]. Some of the most important variables in aquaculture are physical factors, such as temperature and turbidity, and chemical factors, such as dissolved oxygen, salinity, pH, and various forms of inorganic nitrogen, and must be measured on a regular basis [9]. These variables can have minor changes that can affect fish behavior; they include feeding, schooling, swimming, courtship, aggression, and predator avoidance. In addition, stress or adaptive responses such as avoidance, exploration, or anxiety-like behavior can be evoked by these changes [10].

The sustenance of long-term prosperity and productivity of aquaculture practices relies on the maintenance of the correct water quality. Poor or unsuitable water conditions commonly cause physiological imbalances, a drop in the use of feed, poor growth, and higher susceptibility to infectious diseases in cultured fish [11]. The pH, ammonia level, and dissolved oxygen are critical parameters that affect the internal biochemical balance and the metabolic efficiency of fish [12]. Severe stress responses cause vital organs such as the liver, gills, and kidneys to be impacted, and this happens when oxygen levels become depleted or when the levels of ammonia and nitrite become very high beyond the tolerance threshold [13]. These physiological imbalances are a major cause that results in severe financial challenges to aquaculture producers and ultimately affects the health and the market value of fish [14]. Accordingly, maintaining the health of the habitat in which fish can grow, breed, and survive should pass some control over water parameters. Understanding the optimal relationship of fish physiology and water quality can be used to develop management strategies that will improve welfare and profit in aquaculture [15].

Traditional ways to monitor the water constituents of aquaculture tanks are expensive and time-consuming. Farmers are required to manually collect water samples from tanks and send them to laboratories for tests using methods like a chemical kit that tells how acidic it is and its ammonia level [16].

Unluckily, this is not an easy task since it is hard to keep the aquatic ecosystems stable due to the absence of real-time data when using this method [17]. The Internet of Things (IoT) has massive benefits, and its use is transforming the way we live and work entirely [18]. Water quality management and assessment models now require an IoT-based approach, and the significance of such solutions has increased with the modern development of information and communication technology [19].

The application of IoT in aquaculture has demonstrated a tremendous potential in ensuring optimum water quality, enhancing overall productivity, as well as monitoring fishponds. To ensure healthy aquatic life conditions and reduce fish stress and mortality, global food industry aquaculture is one of the rapidly expanding industries [20]. The ease and affordability of integrating Internet of Things devices have been enhanced by cheap and relatively high-performance computer hardware and wireless communication technologies, which have led to their strong growth [21].

In the field of health and life sciences, artificial intelligence (AI) has become an emerging technology, using machine learning and in silico methods to predict, diagnose, monitor, and track patient conditions, as well as to discover and identify new drugs [22-24]. In aquaculture, AI-based predictive models are increasingly being used in fish disease detection and monitoring water quality conditions, as well as optimizing fish health management practices to promote sustainable production [25, 26]. Methods of predicting water quality are also important to reduce the detrimental environmental impact of aquaponic systems. Practitioners can prevent the occurrence of eutrophication of water bodies by reducing the flow of nutrients into the environment through proper prediction of water parameters [27]. This narrative review aims to present a coherent review of the IoT-based water monitoring systems in aquaculture. It concerns strategies of data management, hardware elements, sensor technologies, communication algorithms, and system design. Other future directions and challenges of integrating IoT with machine learning (ML) and artificial intelligence (AI) to manage intelligent aquaculture are also discussed in the paper.

Importance of water quality monitoring in aquaculture

To manage aquaculture in a sustainable and profitable way, water quality needs to be monitored. Aquaculture industry farmers and producers can identify, monitor, and act on changes in critical physico-chemical parameters before they cause permanent biological changes are essential to the continued expansion of aquaculture production globally [28, 29]. Physiological stress response to cultured fish and other aquatic organisms can occur with only minor changes from optimal ranges specific to each species. They are the parameters like dissolved oxygen (DO), pH, temperature, ammonia, nitrite, nitrate, salinity, turbidity, and carbon dioxide, which have to be measured consistently and accurately [30, 31].

Limitations of traditional water quality monitoring

Traditional water quality monitoring techniques, such as manual sampling and laboratory chemical analysis, are expensive and time-consuming and cannot provide the information needed for modern aquaculture management – the information required to be continuously available and in real-time [32, 33]. Significant delays in data gathering happen through manual techniques, so abrupt changes in water conditions, like a sharp decline in dissolved oxygen brought on by algal blooms or the buildup of metabolic waste products, may remain unnoticed until fish mortality starts [34, 35]. Both small-scale and commercial producers may suffer disastrous financial losses because of such incidents. Continuous, sensor-based monitoring of water conditions directly addresses these constraints by providing round-the-clock monitoring [36, 37].

Need for advanced monitoring system

Early warning systems with electrochemical and optical sensors can detect dissolved oxygen changes within seconds and alert the farmers via cloud dashboards or mobile apps to take action, such as activate aerators, adjust feeding timings or switch water exchange ratio [38, 39]. Research has shown that farms with automated water quality monitoring systems perform better than those relying solely on manual monitoring systems in growth performance, feed conversion efficiency, and mortality rates [40, 41].

Preventing crises also yields longitudinal datasets that can be analyzed by machine learning algorithms to look for seasonal trends, detect abnormalities, and make very precise predictions of future water quality conditions [42, 43]. Predictive modelling of previous sensor data can be used to allow farm managers to make management decisions in advance of warm weather events, like reducing stocking density, or installing aeration systems before nocturnal oxygen minima are expected [44, 45]. The industry's ability to safeguard its biological resources and financial investment has fundamentally changed with this move from reactive to predictive aquaculture management [46, 47].

The increasing stresses of climate change are creating changes in temperature, precipitation and extreme weather events, all of which are very relevant to the physicochemical stability of aquaculture ponds and tanks, making water quality monitoring more imperative [48, 49]. Without robust monitoring frameworks in place, in real-time, aquaculture is highly vulnerable to these climate drivers, which may undermine food security and the livelihoods of the millions of people around the world who rely on the industry [50, 51].

Health impact of good water quality on fish

Water quality and fish health are directly related, with a multi-dimensional and significantly meaningful impact on the productivity and sustainability of aquaculture operations [52, 53]. Fish are ectothermic animals with all their metabolic functions sensitive to the water temperature, dissolved oxygen, pH, nitrogenous compounds, and other water parameters [54, 55]. Therefore, maintaining optimal water quality conditions is not only a management preference but a biological necessity that will ensure the welfare of the fish, their normal physiological function, immune competence, and productive performance [56, 57].

Effect of dissolved oxygen on fish health

Dissolved oxygen is undoubtedly the most important water quality parameter for fish health and is essential to all energy-dependent physiological processes and aerobic respiration [58, 59]. Chronic exposure to suboptimal dissolved oxygen concentrations (hypoxia) causes disadvantage to gill function, feed intake, immune responses, growth, and, in extreme cases, mass mortality events [60, 61]. Fish reared in well-oxygenated water have consistently shown better feed conversion ratios, growth rates, and lower prevalence of bacterial and parasitic infections, and reduced levels of stress hormones like cortisol in their blood [62, 63].

Effect of temperature on fish physiology

Temperature has a significant effect on most aspects of fish physiology such as enzyme activity, metabolic rate, reproductive function and immune system function [63, 64]. The different fish species have their own preferred thermal range for optimum growth and immune function, and deviations from this range, both above and below, lead to thermoregulatory stress response mechanisms that also channel energy away from growth and reproduction [65]. High temperatures also hasten the breakdown of pond contents, boost microbial activity, and lower oxygen solubility, leading to a further increase in the physiological stress placed on fish, both by increasing oxygen consumption and decreasing the amount of oxygen present in the pond water [66].

pH importance for fish health

The pH value of aquaculture water has a significant influence on the biochemical equilibria of nitrogenous compounds, on the availability of essential minerals, and on gill epithelial tissue integrity [67, 68]. Fish reared at proper pH (usually 6.5–9.0 for most cultured species) exhibit a normal osmoregulatory response, normal erythrocyte morphology, and a functional mucosal barrier as the first line of defense against pathogens attacking them [69, 70]. On the other hand, acidic conditions (pH < 6.0) can damage gills, impair ion transport and cause an increased susceptibility to gill hemorrhage, and alkaline extremes (pH > 10.0) can lead to ammonia toxicity and corneal damage [71].

Disease susceptibility and toxicity due to ammonia in fish

Ammonia is one of the most toxic N compounds in aquaculture systems, which is produced by the catabolism of protein and the breakdown of organic wastes by microflora [72]. The toxic form is un-ionized ammonia (NH_3), which can readily pass through gill membranes and interfere with neurotransmitter function, leading to convulsions, loss of osmoregulatory control, and death at concentrations above those specific to the species. Long-term exposure to sub-lethal ammonia levels leads to a weakened immune system in fish, making them more susceptible to diseases caused by opportunistic pathogens such as Aeromonas hydrophila and Vibrio spp., which are responsible for significant outbreaks of disease and economic losses in aquaculture around the world [73, 74]. Therefore, good water quality, achieved by using suitable feeding systems, densities, water exchange and biofiltration, has a direct influence on the immune health and disease resistance of fish in culture [75, 76].

Effect of aquaculture water quality on human health and food security

Food safety and human health concerns

However, the quality of the water used to rear fish is far beyond the scope of the aquaculture facility and has significant impacts on human health, food safety, and food security [77, 78]. With the expansion of aquaculture as the predominant commodity to feed the growing global population, the nutritional quality, microbiological safety and chemical safety of the seafood available to consumers is increasingly influenced by the conditions under which fish are farmed The effects on human health in aquaculture systems are multifaceted and related to each other in a complex way, with environmental contamination of fish, the growth of zoonotic pathogens, unnecessary use of antibiotics and other veterinary chemicals, and release of effluents with high nutrient levels. Another important route of aquaculture water quality influencing human health is microbiological safety [79-81].

IoT-based monitoring for food security

The implementation of the real-time water quality monitoring systems based on IoT is a key technological solution, which can not only enhance the safety and quality of aquaculture products but also lower the environmental impact of the aquaculture system and enhance the role of the aquaculture industry in sustainable food security in the world [16, 82].

Review Methodology

In order to evaluate IoT-based monitoring systems used in aquaculture, a comprehensive review of the literature took place. The search in Scopus, Web of Science, IEEE Xplore, Google Scholar, and PubMed was done with such keywords as: IoT in aquaculture, fishpond monitoring, water quality monitoring, smart aquaculture, and AI/ML in aquaculture. They included the studies on sensor technologies, water quality parameters, or AI/ML integration released in English during the period of 2015-2026. Out of 44 articles, 35 relevant articles were selected to be reviewed in more detail. After the process of eliminating duplicates, screening of titles and abstracts, and application of exclusion/inclusion criteria had been conducted, relevant papers were included, and irrelevant papers were removed. The literature search and selection process is summarized in **Fig. 1**.

Each study provided data on hardware platforms, species of fish to be observed, and water quality parameters, biological/ecological impact, connectivity solutions, and significant results. Subsequently, the data was analyzed to identify the gaps in the existing IoT-based aquaculture systems, cost-effectiveness, and technological tendencies.

IoT-based fishpond monitoring: Literature review summary

Importance of IoT in Modern Aquaculture

Aquaculture has been using the Internet of Things (IoT) more and more in recent years to enhance fishpond management and monitoring. IoT-based solutions are being used to automatically monitor important factors, including temperature, pH, dissolved oxygen (DO), and turbidity, as the need for efficient water quality control increases. These elements are essential for maintaining the health, survival, and growth of fish [83]. IoT, cloud computing, and artificial intelligence (AI) have created new opportunities for data-driven aquaculture management. By using these technologies, farmers may monitor pond conditions from a distance and take prompt action to stop the decline of water quality. In addition to increasing output, this integration reduces human error and promotes more profitable and sustainable aquaculture methods [84].

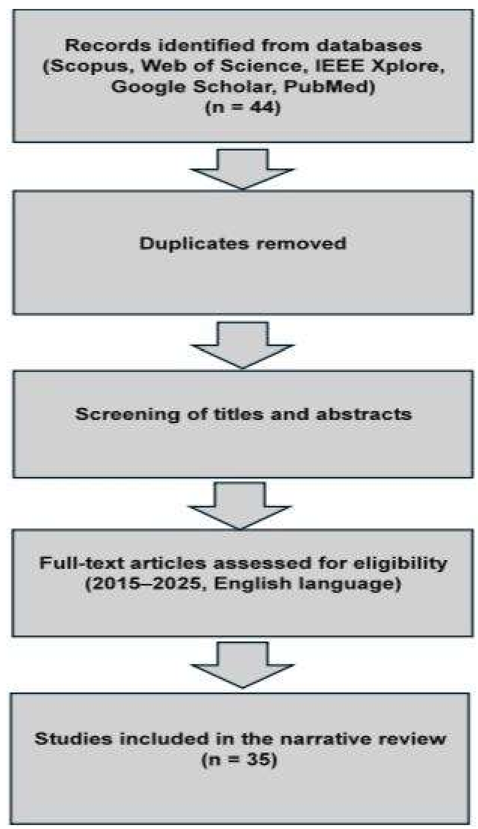

Fig. 1: Flowchart illustrating the literature search, screening, and selection process used in this narrative review of IoT-based fishpond monitoring systems.

Internet-of-things (IoT)-based solutions are adopted to monitor the important parameters automatically and continuously, and the parameters include temperature, pH values, DO (dissolved oxygen), and turbidity. These factors are necessary to maintain the sustainability and health requirements of fish. IoT technology has opened doors to the application of cloud computing and AI to control the water quality efficiently [85]. The general architecture of an IoT-based fishpond monitoring system is illustrated in **Fig. 2**.

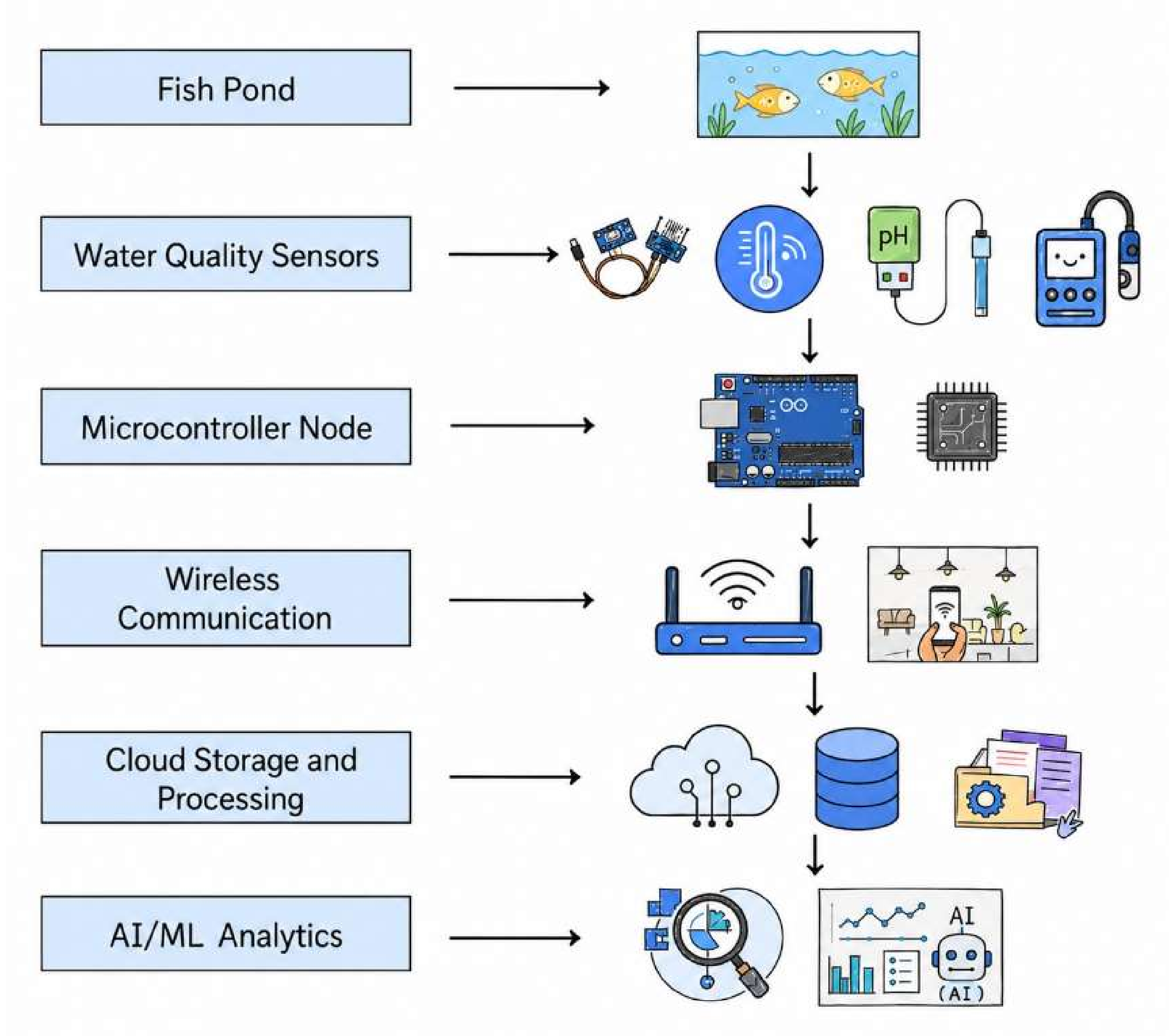

Fig 2. Architecture of an IoT-based fishpond monitoring system showing water quality sensing, edge-level data acquisition, wireless communication, cloud-based storage and processing, and AI/ML-driven analytics for smart aquaculture management.

Architecture of IoT-based fishpond monitoring systems

Refined water is obtained through the application of IoT technology. By adopting the technologies, the farmer will be able to check the pond condition from afar and will take immediate actions to halt the degradation of the water quality. In doing so, the output may increase along with profitable fishery practices [85]. The typical operational workflow of an IoT-based fishpond monitoring system, from sensor data acquisition to cloud-based analysis and decision support, is illustrated in **Fig. 3**.

A summary of various documented IoT-based pond monitoring systems that were documented from 2020 to 2024 is provided in **Table 1**. For a stable water condition to be realized, an exhaustive study of the pond system based on the IoT was carried out

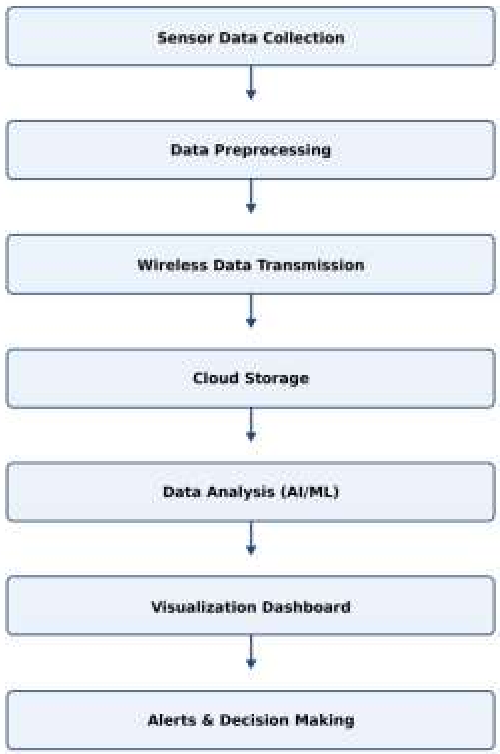

Fig. 3: Workflow of an IoT-based fishpond monitoring system showing data acquisition, transmission, cloud storage, analysis, visualization, and alert generation.

by [86] through the usage of underwater sensors linked to Wi-Fi and cloud networks. The development of an intelligent fish-adjusting structure in fish ponds through an Arduino-based system resulted in fish survival rates through the effort of [87]. Another move towards the automation of aquaculture was brought about by [88], who designed an AquaBot, a robot that uses the Internet of Things technology for the purpose of gathering information from the aquatic environment. Additionally [89], demonstrated the ability to control temperature, pH, and dissolved oxygen in a grouper culture pond using a wireless Arduino.

Cost-effective solutions

There have been several research works carried out to make IoT more affordable. [90] designed a system that was affordable and would benefit small fish farmers, using Raspberry Pi B+ and pH, temperature, and DO sensors that measured and stored information in a MySQL database. In a bid to make the system more affordable in terms of maintenance, [90] designed a system using Arduino, which is affordable and is connected to cloud storage and phones. [91] designed a system using ESP32 to control an Android that would, depending on the pH and turbidity levels in the water, automatically fill the fish pond with water. [92] examined the use capabilities of the cloud-based platform ThingSpeak in the African catfish ponds to detect the amount of nitrates and ammonia to control the health-risk accumulation. [93] were able to expand the use capabilities owing to the multi-parametric sensors to check the availability of CO_2, salinity, nitrates, nitrites, or the orthophosphates. This is the neutral form to directly implement the use of smart aquaculture, supported by the requirements of Industry 4.0. In order to achieve accurate data calibration and reliable performance, [94] introduced the compromise model through the use of inexpensive sensors and concentrated on the requirements regarding accuracy and availability through the use of the technology-based ESP8266.

Biosensors and wearable technologies for fish health assessment

Biological monitoring advancement has expanded the smart aquaculture from water quality monitoring to evaluating fish health and welfare [95]. In aquaculture biosensors, helps to enhance as these are used to detect challenges, including climate change, sea-level salinity increase, temperature changes, ocean acidification, precipitation patterns changes, ammonia toxicity, infectious diseases, and stress factors [96]. A wearable bioimpedance-based deep learning framework used for fish stress monitoring and health assessment using WBIA signals, which monitor fish stress [97]. Accelerometry is used to assess swimming, hovering, and other behavioral assessments in fisheries [98].

Recent Advances in IoT-Based Fishpond Monitoring

Table 2 presents IoT communication protocols with trade-offs among range, data rate, energy efficiency, and deployment cost. While LoRaWAN and NB-IoT are ideal for long-range, low-power

Table 1: IoT-Based Fishpond Monitoring System

No.	Author & Year	Platform / Hardware	Fish Species	Parameters Measured	Biological / Ecological Impact	Connectivity / Cloud	Key Outcome
1	[86]	IoT sensors + underwater sensors	General	pH, Dissolved Oxygen, Temperature, Turbidity	Maintains optimal water conditions for fish health and growth	Wi-Fi + Cloud Server	Thorough analysis of Internet of Things pond monitoring systems
2	[99]	AquaBot Robot + IoT Sensors	General	Temperature, pH, Dissolved Oxygen, Turbidity	Supports healthy fish environment through automated monitoring	Cloud + Mobile App	Automated intelligent fish-pond robot with instantaneous feedback
3	[100]	Wireless Sensors + Arduino	Grouper (Epinephelus spp.)	pH, Temperature, Dissolved Oxygen, Water Level	Maintains optimal environment (22–28 °C, pH 7–9, DO ≈ 5 mg/L); reduces mortality	Cloud Dashboard + Wi-Fi	Robotic sampling and water quality monitoring
4	[101]	Raspberry Pi B+ + Sensors (DS18B20, DO, pH)	General	Temperature, pH, Dissolved Oxygen	Maintaining parameters prevents stress, disease, and mortality	Wi-Fi + MySQL Database	An inexpensive Internet of Things model for monitoring water quality in real time
5	[102]	Arduino + Sensors + Mobile App	General	pH, Temperature, Water Level	Ensures good health and eco-friendly pond environment	Wi-Fi + Cloud Database	Economical IoT-based pond management system
6	[103]	ESP32 module + Sensors + Android App	Carp (Cyprinus carpio)	Temperature, pH, Turbidity	Improves survival rate; poor water quality causes stress and mortality	Wi-Fi + Firebase	Automatic water replacement and real-time monitoring
7	[104]	ESP32 + DF Robot Sensors	African catfish (Clarias gariepinus)	Temperature, pH, Dissolved Oxygen, Turbidity, Ammonia, Nitrate	Maintains ideal pond conditions; prevents ammonia/nitrate toxicity	ThingSpeak IoT Cloud	Real-time monitoring of an IoT-based aquaponics system
8	[105]	ESP8266 + Low-cost sensors	General	pH, Dissolved Oxygen, Temperature	Accurate low-cost system ensures water quality maintenance	IoT Cloud	Increased precision in sensor calibration

healthcare monitoring applications, Wi-Fi and 5G are better for data-heavy medical services, like telemedicine and medical imaging. Wearable and body-area sensor networks are the networks of choice for ZigBee and BLE networks due to their low energy consumption and simplicity of deployment.

AI-based predictive systems

AI is widely used in computational biology ([116] such as computer-aided drug design[117-120], virtual screening and vaccine discovery [121-125]. Artificial intelligence integrated with IoT is used to monitor water quality and involves a prediction system for water quality data [126]. This system monitors water quality and enhances the survival rate of fish by reducing mortality [127]. Previous studies rely on sensor-based data acquisition and cloud storage, but recent developments integrate artificial intelligence, including machine learning, deep learning, and data analysis, to enhance prediction and system responsiveness. A summary of these models is given in **Table 3**.

Role of IoT and AI technologies in climate-resilient aquaculture systems

Climate change, including rising temperature, erratic rain pattern extreme weather changes, has become a global threat [132]. However, incorporating AI with climate-adaptive strategies can transform food production and resource management, and build resilience by establishing adaptation practices such as crop diversification, remote sensing, analysis of yield, efficient water management, agroforestry, conservation

Table 2: Summary table comparing the advantages and limitations of different IoT communication protocols

Reference	Protocol	Range	Data Rate	Power Consumption	Advantages	Limitations	Healthcare Applications
[26, 106]	LoRaWAN	2–15 km	0.3–50 kbps	Very Low	Long communication and battery life, low cost, ideal for remote sensing	Low data rate, higher latency, unsuitable for multimedia transmission	wearable sensors, Remote monitoring, used in rural healthcare
[107, 108]	Wi-Fi	20–100 m	Up to several hundred Mbps	High	High throughput, low latency, existing infrastructure	High energy consumption, limited coverage	Hospital information systems, medical imaging, telemedicine
[109, 110]	ZigBee	10–100 m	250 kbps	Low	Low power, mesh networking, scalable sensor networks	Short range, limited bandwidth	Body sensor networks, smart healthcare devices
[110, 111]	NB-IoT	Several kilometers	Up to ~250 kbps	Very Low	Excellent indoor penetration, secure communication, long battery life	Cellular subscription required, moderate latency	Smart hospitals, remote patient monitoring
[112, 113]	Bluetooth Low Energy (BLE)	10–100 m	Up to 2 Mbps	Very Low	Ultra-low power, smartphone compatibility, low cost	Limited range, fewer simultaneous connections	Fitness trackers, wearable biosensors, glucose monitors
[114, 115]	Cellular (4G/5G)	Nationwide	Mbps–Gbps	Moderate–High	High speed, very low latency (5G), mobility support	High infrastructure and operational costs	Telemedicine, AI-assisted diagnosis, emergency healthcare

agriculture, climate-resilient crop varieties, and early warning systems [133, 134]. Artificial intelligence analyzes long-term environmental datasets to predict coming adverse events, such as stress due to an increase in temperature, low oxygen, harmful algal blooms, and disease outbreaks, to enhance climate resilience [135, 136]. In Aquaculture, predictive AI models can support management strategies, including feeding schedules optimization, aeration control, adjustment of stocking density, and emergency response system planning [137].

AI applications in other life sciences domains

The advancement of artificial intelligence has not only transformed aquaculture but also plays a significant role in other life science domains. Artificial Intelligence is used in healthcare for various purposes, including medical image analysis, disease detection, drug discovery, personalized medicine, and patient monitoring. AI ethics in healthcare [138, 139]. In agriculture, AI, especially machine learning, plays an important role in analyzing farm finance, precision farming by yield prediction and harvest planning, irrigation management, crop disease management, and pest control [140, 141]. Similarly, in livestock production, AI is used for animal health and behavioral monitoring and productivity optimization [142-144].

Table 3: Summary of prediction and system responsiveness models

No	Author & Year	Platform / Hardware	Fish Species	Parameters Measured	AI / ML Method	Biological / Ecological Impact	Connectivity / Cloud	Key Outcome
1	[128]	Arduino + ML + Cloud	General	Temperature, pH, Dissolved Oxygen	ML-based decision model	Ensures species survival via AI decisions	IoT Cloud + Decision Model	Real-time IoT monitoring with AI-driven control
2	[129]	IoT sensor system	General	Temperature, DO, pH, Salinity, CO_2, Ammonia, Nitrate, Nitrite, Orthophosphate	Data analytics / AI-enabled Industry 4.0 system	Improves production, reduces disease and mortality	Wi-Fi + Firebase Cloud	Smart aquaculture with predictive analytics
3	[130]	Solar-powered IoT buoy (Arduino Mega 2560, LoRa, GPS, accelerometer, Li-ion battery, solar panel, RS-485 sensors)	Offshore aquaculture	Temperature, DO, salinity, water velocity, flow direction	LSTM (temperature & velocity prediction) + Nonlinear regression (flow tube velocity estimation)	Enables early warning of environmental changes, reduces fish stress and mortality,	LoRa + Shore server (MySQL) + Mobile App	Low-cost AI-enabled buoy with short-term water quality prediction and real-time monitoring
4	[131]	DF–DRL aquaculture system	WSN, Arduino Uno, Firebase, MQTT, mobile app	Temperature, pH, turbidity	Deep Learning + Deep Reinforcement Learning + Data Fusion	Maintain water quality enhances fish survival rate	Wi-Fi-enabled WSN + MQTT-based communication + Firebase Cloud database + Android application interface	3-layer fusion (signal-feature-decision), binary classification (“normal/not normal”), improved decision-making over traditional systems

In molecular biology and genomics, AI provides gene expression analysis, protein structure prediction, discovery of biomarkers, and genome-wide association studies, including gene editing [145, 146]. Environmental sciences use AI for ecosystem assessment, biodiversity, and climate change monitoring [147, 148]. Artificial intelligence-based computational methods, such as network pharmacology, molecular docking, ADMET prediction, and molecular dynamic simulation, are used for drug target identification and bioactive compound screening [116, 149, 150]. These strategies have great potential to advance drug discovery and could be used in aquaculture to enhance fish health and disease management.

Gaps and future perspective

Despite the above advancements, there still remain areas of gaps in the current research. Despite the long-term implications of water health, Nutrients such as ammonia, nitrates, phosphates, or CO_2 are often ignored by current models that focus primarily upon the basic factors of temperature, pH, DO, or turbidity in the water. Additionally, very few studies reveal correlations among biological endpoints of fish growth rate, stress response, or disease prevalence and data from the environment [94]. Although some systems have recently begun to involve AI and machine learning [87], applications remain limited, with very few that can predict in real time. The second major issue is related to connectivity, particularly in rural areas [151]. Aquaculture uses energy-efficient alternatives such as LoRa and LPWAN networks, which remain understudied [152]. Finally, direct monitoring of the well-being of fish, whether stressed or hungry, is limited because integrated systems that link environmental and biological sensors remain scarce [153].

Thus, the reviewed literature not only underlines the requirement for even more intelligent, integrated, and adaptive systems but has also displayed instances where IoT is already immensely helpful in aquaculture monitoring. To create an all-encompassing and sustainable IoT framework for aquaculture, future research should concentrate on emerging technologies such as digital twins and edge AI for aquaculture management, integrating biological and environmental sensing, AI-powered predictive analytics, and low-power communication technologies.

Conclusion

The potential of IoT in aquaculture has remained promising towards ensuring ideal water quality and enhancing the total productivity, as well as monitoring of fish ponds. To ensure a healthy aquatic environment and reduce stress and mortality of fish, the given review focuses on the capabilities of the systems enabled with the IoT to automatically measure the key parameters such as temperature, pH, dissolved oxygen, turbidity, and, in some cases, nutrients such as ammonia and nitrates. The integration with cloud computing, artificial intelligence, and machine learning makes it possible to use data-based decision-making, real-time changes, and predictive management methods. Although these developments have been made, the current systems remain predominantly descriptive, with most of them focusing on basic water properties and often disregarding the biological indicators such as fish growth, behavior, and stress responses. It has continued to have problems of energy efficiency, sensor accuracy, cost-efficiency, and connectivity in rural settings. The solutions of the IoT-based aquaculture in the future should be integrated with biological and environmental sensors, low-power communication systems, and predictive AI/ML to develop intelligent, integrated, and adaptive aquaculture systems. Apart from improving the welfare and survival rate of fish, the technologies will also improve the environmental sustainability and economic viability of the aquaculture operations. Summarily, in smart aquaculture, IoT is a game changer that requires comprehensive and flexible strategies that take to account the biological as well as technological side of fishpond management.

Conflict of interest

The authors declare no conflict of interest.

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