

# New trends in aquaculture monitoring and technologies: a brief review

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**Abstract.** This paper examines recent advancements in aquaculture monitoring and related technologies, focusing on trends from 2020 onward. It reviews articles to analyze monitored parameters, types of aquaculture environments (e.g., open sea, ponds, cages), the presence of control mechanisms, and innovations in monitoring technologies. The study covers systems that solely monitor water quality as well as those incorporating control mechanisms to regulate conditions, emphasizing how controlled systems can optimize production more effectively. Additionally, it also explores communication protocols, highlighting the growing trend toward IoT integration for real-time monitoring and control. The paper advocates for future research to address advanced metrics in aquaculture monitoring. The findings suggest that integrating monitoring with active control mechanisms presents a promising approach to enhancing and sustaining productivity across various aquaculture settings.

**Keywords:** Aquaculture monitoring, Sustainability, Water Quality

## 1. Introduction

Aquaculture is widely regarded as one of the most environmentally sustainable methods of food production, particularly for protein. Initially practiced on a small scale to produce limited quantities of fish, it has a history spanning hundreds of years. However, as the global population expanded, so did the demand for food, prompting increased investment in sustainable food production methods. Aquaculture emerged as a key solution for meeting the growing demand for aquatic-based foods. In the early stages of modern aquaculture, enhancing efficiency became a priority, driving the development of innovations aimed at controlling and maintaining water quality.

To secure and maximize these benefits for present and future generations the Food and Agriculture Organization (FAO) is developing a blue transformation strategic program within its Strategic Framework 2022-2031. Its goal is to enhance the contribution of aquatic food systems in ensuring food and nutrition security by promoting socially, environmentally, and economically sustainable production and value chains [11].

Water quality is critical in aquaculture, directly influencing the growth and health of the produce and significantly impacting the overall efficiency of the facility. Initially, water quality measurements were performed manually, requiring labor-intensive efforts. The introduction of technology for water quality monitoring dates back to the 1970s [12], marking the beginning of automation in aquaculture. Since then, advancements have continued, incorporating new technologies, including the recent adoption of Industry 4.0 concepts. These innovations enable large-scale data collection and processing in real-time, supporting the generation of alarms, corrective actions, insights, and trend detection in farming parameters.

This study presents a comprehensive analysis of recent developments in water quality monitoring for aquaculture, examining monitored parameters, control mechanisms, and communication protocols.

The paper is organized as follows: Section 2 outlines the selection criteria for the articles reviewed; Section 3 presents the analysis of the selected studies; Section 4 discusses the findings; and Section 5 summarizes the results and suggests directions for future research.

## **2. Article selection criteria and results**

This study uses a range of sources, including research articles, review articles and conference papers reporting technological advancements, and practices in aquaculture monitoring and control systems. The authors selected recently published articles from 2020 onward trying to capture how far Industry 4.0 paradigms have been applied to aquaculture. Focusing on recent literature ensures that the information gathered includes the newest monitoring parameters techniques and advancements in automation, IoT and other trends in aquaculture farming.

The articles to be reviewed were collected from the ScienceDirect and EBSCO databases using the keywords “aquaculture data acquisition” for the search. After that the search was further refined resulting in the selection of 10 articles: one from conference proceedings and 9 from journals. Three of these are review articles about smart aquaponics, Industry 4.0 systems and the use of unmanned systems in aquaculture.

## **3. Analysis criteria and results**

The articles were analyzed based on the following criteria: monitored water quality parameters, types of tanks utilized, implementation of process control systems, and communication protocols employed. The gathered information was systematically organized into tables, which are presented in the subsequent subsections.

### 3.1. Water Quality parameters

Table 1 presents the water quality parameters identified in each of the selected papers, emphasizing both frequently monitored and less frequently tracked parameters across various aquaculture systems.

Table 1 concerning water quality parameters in aquaculture, shows a clear focus on monitoring essential parameters for fish health and ecosystem stability, with temperature, pH, and dissolved oxygen (D.O) appearing as the most frequently monitored parameters. These three parameters are critical, as they directly affect fish metabolism, growth, and reproduction, making them essential in maintaining optimal aquatic environments [13]. Parameters like turbidity, salinity, and ammonia are also monitored in half of the articles reviewed. Other parameters, like oxidation-reduction potential (ORP), water hardness (W.H), nitrogen (N<sub>2</sub>), chlorophyll a (Chl. A), and microplastic detection (MP.D), are less commonly monitored, indicating that these metrics may either be relevant to specific types of aquaculture systems or are newer areas of study.

**Table 1 Water Quality Monitored Parameters**

Article	Water Quality Parameters														
	Temp	pH	D.O	CO <sub>3</sub>	Turbid.	Conduct.	Salinity	ORP	W.H	Ammonia	N <sub>2</sub>	Chl. A	W.L	N.D	MP.D
[1], 2023	x						x						x		
[2], 2023	x	x	x	x	x	x	x	x					x	x	X
[3], 2022	x	x	x							x	x			x	
[4], 2022	x	x	x		x	x		x	x				x		
[5], 2024	x	x	x				x			x					
[6], 2021	x	x	x		x	x							x		
[7], 2024	x	x	x												
[8], 2023	x	x	x		x		x								
[9], 2024	x	x	x				x		x	x	x				x
[10], 2024					x								x		

**Caption:**

Temp- - Temperature  
 pH – Potential of Hydrogen  
 D.O – Dissolved Oxygen  
 Turb. – Turbidity  
 Cond. – Conductivity  
 Sal. – Salinity  
 ORP – Oxidation-reduction potential  
 W.H – Water Hardness  
 Amo – Ammonia  
 N2 - Nitrogen  
 W.L. – Water Level  
 N.D – Nitrite Detection  
 MP.D – Microplastic Detection  
 Chl. A – Chlorophyll a

**3.2. Type of tank**

Table 2 below outlines the types of tanks used in each study, distinguishing between controlled and uncontrolled environments to show how tank types' influence monitoring and control strategies in aquaculture systems.

**Table 2 Type of Tank**

Article	Type of Tank	
	Closed	Open sea
[1], 2023	x	
[2], 2023	x	x
[3], 2022	x	
[4], 2022		x
[5], 2024	x	
[6], 2021		x
[7], 2024	x	
[8], 2023	x	
[9], 2024	x	
[10], 2024	x	

The information on Table 2 categorizes aquaculture systems based on whether they are situated in open-sea cages or use closed environments. Out of the ten articles analyzed,

most of them focus on closed systems, with a smaller number examining open-sea settings. This indicates a research trend toward more controlled, enclosed aquaculture systems, which are often easier to regulate and monitor due to reduced environmental variability.

The fewer studies on open-sea cages reflect the challenges associated with these systems, such as exposure to fluctuating ocean conditions, lack of control of water quality and potential environmental impacts. However, open-sea cages offer benefits, including improved water exchange and waste dispersion, making them suitable for certain aquaculture species. This focus on closed systems suggests that researchers are prioritizing studies on systems that allow for tighter control over water quality and environmental parameters, which is especially important for high-density fish farming and sensitive species.

### 3.3. Control

Table 3 summarizes the use of automation in process control across various studies, highlighting whether each article actively integrates automated control systems to manage aquaculture parameters.

**Table 3 Control**

Article	Control	
	Yes	No
[1], 2023		x
[2], 2023	x	x
[3], 2022	x	
[4], 2022		x
[5], 2024		x
[6], 2021		x
[7], 2024		x
[8], 2023		x
[9], 2024	x	
[10], 2024	x	

Table 3 shows whether the aquaculture systems incorporate automated control mechanisms. Out of the ten articles analyzed, slightly fewer than half include control mechanisms (noted as "Yes") that actively manage environmental parameters, such as water temperature, dissolved oxygen, or pH levels. These systems use sensors and actuators to maintain optimal conditions for aquaculture species, allowing for more precise and responsive adjustments.

Conversely, most of the articles focus on systems without active control (noted as "No"), which rely solely on monitoring rather than automated intervention to adjust conditions, relying on manual actions to correct the problems detected. This distribution highlights a growing interest in automation, although traditional monitoring-only setups are the more reported. The trend toward automation in controlled environments reflects the demand for increased precision in aquaculture practices and health standards compliancy.

### 3.4. Communication Protocols

Table 4 shows the variety of communication protocols used for collecting water quality parameters in aquaculture systems.

**Table 4 Communication protocols**

Article	Protocol						
	N.A	HTTP	UART	Ethernet	Zigbee	MQTT	Modbus TCP
Article [1], 2023				x			
Article [2], 2023			x		x	x	
Article [3], 2022	x						
Article [4], 2022	x						
Article [5], 2024		x					
Article [6], 2021	x						
Article [7], 2024			x				
Article [8], 2023		x					
Article [9], 2024							x
Article [10], 2024	x						

Caption: N.A- - No protocols mentioned

Table 4 outlines the communication protocols utilized across the aquaculture monitoring systems examined in each article. Of the protocols analyzed, Ethernet and HTTP appear more frequently, signaling their common use for stable communication in aquaculture environments where reliable data transfer is crucial. UART (Universal Asynchronous Receiver-Transmitter) and Zigbee are mentioned in a couple of studies, likely chosen for applications requiring more straightforward or wireless communication in controlled, short-range environments.

Conversely, Modbus TCP and MQTT are referenced in fewer studies. Modbus TCP is typically used for industrial automation, and MQTT, a protocol optimized for Internet of Things (IoT) applications, these suggest more advanced systems that may focus on scalable and efficient data handling. The diversity of protocols reflects the varying requirements in aquaculture systems, ranging from simple setups to advanced IoT-integrated environments.

### 3. Results analysis

The articles analyzed in Table 1 track numerous parameters related to water quality, with temperature (Temp), dissolved oxygen (D.O.), and pH being the most consistently monitored across studies. These core parameters are essential in aquaculture, as they influence fish metabolism, respiration, overall health and fish reproduction. There are also applications reported [3] that analyze the behavior of fish using artificial vision based only in temperature and dissolved oxygen measures. Other frequently monitored indicators include conductivity (Cond.) and turbidity (Turb.), which provide insights into water clarity and the concentration of dissolved substances. Less commonly tracked parameters are salinity (Sal.), oxidation-reduction potential (ORP), and ammonia (Amo). Specialized metrics like microbial density (MP.D) and chlorophyll a (Chl. A) appear in only a few studies, emphasizing the role of water chemistry and microbiological content in controlled environments.

In [2], the authors highlight the importance of monitoring nitrites, especially in land-based aquaculture, and detecting microplastics due to the health issues they can cause in both farmed species and potentially in human consumers. Although these parameters are not currently measured in most aquaculture farms, likely due to the lack of appropriate sensors, it is expected that they will become increasingly common in the future as suitable nitrate and microplastics sensors become available.

Most of the applications reported involve on-site measurements using fixed sensing equipment. However, unmanned vehicle monitoring and feeding is a recent concept that could be adopted in future aquaculture, especially for operations in open seas or large tanks where understanding the 3D distribution of water quality parameters is crucial. The use of unmanned vehicles arises from the need to obtain homogeneous measurements of water quality parameters. These vehicles enhance aquaculture by allowing precise, real-time monitoring of water quality and fish health while minimizing human labor and risk. Unmanned vehicles can also feed the fish in various locations of the cage, ensuring feeding accuracy and reducing waste.

The type of aquaculture setting—whether open-sea, pond, or cage was also a factor to consider, open-sea environments are influenced by dynamic oceanographic factors such as currents and tides, which can impact water quality and fish welfare. Conversely, ponds require different management protocols due to their more controlled but often crowded environments, making specific monitoring systems and strategies more applicable. By including a variety of aquaculture environments, this review captures a range of approaches and protocols, ensuring the findings are broadly applicable across different types of aquaculture operations.

Most of the aquaculture applications reported use technology only to monitor water parameters and only a few of them acts automatically upon the measures taken.

The use of actuators in aquaculture monitoring systems can play a vital role, particularly in practices like controlled feeding and water recirculation. Actuators automate mechanical responses, such as adjusting feed dispensation rates based on real-time sensor data, which helps optimize feeding schedules and reduce waste, thus supporting sustainable practices. In water quality management, actuators can regulate pumps and valves within recirculating aquaculture systems, enabling precise control over water exchange rates and oxygenation. This level of automation maintains stable water parameters, minimizing stress on aquatic species and improving overall production efficiency. Thus, it is expected that these advantages are incorporated resulting in an increase of fully automated aquaculture farms.

Analyzing the communication protocols used was also an essential criterion for understanding new trends in Industry 4.0 within this application domain. Articles covering controlled environments (those with high levels of automation or data analytics integration) are considered nowadays particularly valuable because they provide consistent automated action responses in the presence of alarms or the need to regulate water quality and on the other hand the collection of big amounts of data leads to a new trend where the behavior of fish, water quality, etc can be predicted based on the use of deep learning and other artificial intelligence data analysis techniques. At the same time, studies on semi-controlled or traditional systems provide valuable insights into how fundamental monitoring techniques can be adapted or integrated with newer technologies.

The protocols vary in complexity and functionality, ranging from general-purpose standards like HTTP, as reported by some articles, to more specialized protocols such as Modbus TCP and MQTT. These specialized protocols offer standardized and efficient communication, particularly for devices in industrial settings. In articles where the use of Ethernet, UART, and HTTP was reported, data transfer is straightforward and widely compatible, making these protocols suitable for simpler monitoring setups. Meanwhile, articles that reference advanced protocols like Zigbee and MQTT suggest a focus on Internet of Things (IoT) integration, which supports wireless communication and is more energy-efficient for real-time monitoring.

#### **4. Conclusion**

Water quality is the primary focus of aquaculture monitoring. Reviewing articles that address a wide range of water quality parameters provides a comprehensive understanding of the monitoring requirements in modern aquaculture. Including studies covering

diverse parameters helps identify the most frequently monitored factors and the latest trends in the industry.

As observed, the focus in many studies remains on traditional parameters—temperature, pH, and dissolved oxygen—since these are foundational for aquatic species health and productivity. However, there's an emerging interest in tracking additional parameters, such as chlorophyll-a, nitrate and microplastic levels, which represent a shift toward addressing broader environmental impacts and sustainability concerns within aquaculture. Microplastic detection, for instance, could gain significance as awareness grows regarding pollution in aquatic ecosystems.

In most aquaculture farms, data is still collected manually with long time intervals and also their actions (e.g. fish feeding) are manual, so future research will likely expand both in monitoring scope and automation.

Monitoring alone can provide valuable insights, but systems with integrated control mechanisms can respond dynamically to water quality fluctuations, potentially improving productivity and environmental outcomes. This trend indicates a likely future where more automated systems could allow real-time adjustments.

Additionally, adopting more advanced, low-power IoT protocols could further streamline data collection and control in diverse settings. This would enable the collection of large amounts of data, which would be easily available in real-time for monitoring, control, and predicting or anticipating important events

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