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RECEIVED 08 March 2025

ACCEPTED 29 July 2025

PUBLISHED 15 August 2025

CITATION

Rodríguez MCB, González CEM,
Almanza EDC, Rodríguez CG, Regino-
Vergara JÁ and López-Padilla A (2025)
Benefits and challenges of the internet of
things in aquaculture production: a literature
review.

Front. Sustain. Food Syst. 9:1590153.
doi: 10.3389/fsufs.2025.1590153

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Benefits and challenges of the internet of things in aquaculture production: a literature review

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To advance research that enables the integration of Industry 4.0 technologies and enhances competitiveness in the aquaculture sector, it is crucial to review the existing literature on the applications, architecture, and challenges of the Internet of Things (IoT) in production processes. This study employs a structured five-phase methodology, which includes the formulation of three research questions, a targeted search for relevant information using key descriptors in the Dimensions database, the establishment of inclusion and exclusion criteria, the assessment of the relevance and quality of selected contributions, and the synthesis of findings. The analysis identified key factors affecting production, as well as the architectural components essential for monitoring water quality. The results indicate that the IoT presents a significant opportunity for growth in the sector. Nevertheless, several challenges remain, including limited access to and design of devices, inadequate connectivity for data transmission, data storage constraints, high energy consumption, sensor calibration issues, and poor-quality sensory data that can impede effective decision-making. The study concludes that addressing this technological gap will require the development of low-cost, yet highly efficient, hardware and software solutions tailored to the specific needs of the aquaculture industry.

KEYWORDS

4.0 technologies, aquaculture, fish farming, internet of things—IOT, water quality

1 Introduction

The aquaculture sector is a growing industry characterized by the use of specialized techniques and procedures for the breeding, rearing, and fattening of fish and other aquatic species in controlled environments such as ponds, rivers, and other water-based systems (Angarita-Zapata et al., 2021). This sector plays a highly significant role in the global food supply chain, emerging as an innovative and sustainable alternative to the overexploitation of wild fishery systems (Gladju et al., 2022). Furthermore, in response to the challenges governments face in ensuring food security and strengthening food sovereignty within communities, the Food and Agriculture Organization of the United Nations (FAO) reported that, in 2022, aquaculture production reached 130.9 million tons, representing 51% of global aquatic animal production. For the first time, this figure surpassed that of capture fisheries in terms of volume, establishing aquaculture as a key source of high-quality nutritional protein

(Yue and Shen, 2022), particularly in regions where traditional fishing fails to meet population demands.

On the other hand, the competitive growth of the aquaculture sector can significantly contribute to the achievement of the Sustainable Development Goals (SDGs), as it not only serves as an alternative to ensure food security (SDG 2) but also promotes decent work and economic growth (SDG 8), encourages responsible production and consumption (SDG 12), and supports the conservation of life below water (SDG 14). In this regard, its potential for job creation can simultaneously contribute to the achievement of SDG 1, which focuses on poverty reduction in emerging countries, as demonstrated by the study presented by Troell et al. (2023).

Nevertheless, to realize this potential completely, the sector must overcome several operational challenges. Traditionally, water quality monitoring relies on manual methods to assess physicochemical variables, often yielding inaccurate or inconsistent results. These methods typically require significant investment in human resources, thereby increasing overall production costs (Chen et al., 2022). This process of manually recording observational data and later transferring it to spreadsheet applications for analysis is often hindered by inadequate formatting, which limits its effectiveness. As a result, a growing number of aquaculturists are turning to data-driven approaches to improve farm management and optimize operational procedures.

Moreover, fish farming requires a well-structured supply and production system, the implementation of appropriate culture structures, adherence to good management practices (particularly in food and sanitation), continuous monitoring of input sources and selection, and, importantly, timely and efficient marketing strategies (Dias et al., 2020).

The adoption of 4.0 technologies such as high-resolution satellite imagery, artificial intelligence (AI), data mining, machine learning (ML), and the Internet of Things (IoT) across various sectors has led to the emergence of Aquaculture 4.0. This concept refers to the integration of advanced technological tools for the precise monitoring of processes and product quality, aiming to enhance efficiency and competitiveness (Gladju et al., 2022). Due to the inherent biological unpredictability of aquaculture, which carries considerable risk, increasing reproducibility in farming operations is essential. Standardized precision interventions designed to elicit predictable responses can achieve this (Valentia et al., 2021). To ensure sustainability and increase profitability, it is necessary to employ technologies that allow the interpretation of data in an accessible and readable format for fish farmers to understand and make decisions; this requires automatic mechanisms for data capture, processing, and visualization (Lan et al., 2023).

The IoT, defined as an internet-based network that connects physical and virtual objects through standardized, interoperable communication protocols, is one of the key emerging technologies addressing challenges in the aquaculture sector. This technology has widely penetrated most aspects of human life, including fish farming, an industry characterized by large areas that require rigorous attention and control (Shi et al., 2019). With the sustained improvement of these technologies, this industry has gradually evolved from traditional practices to a smart model. In this approach, employing sensors to monitor changes in water quality and other environmental parameters enables the automatic adjustment of operational plans, which significantly enhances productivity and reduces costs (Cao et al.,

2022). These IoT devices capture and transmit data to the internet in real time, typically via wireless communication networks. Once stored in servers or the cloud, access to the data is available for analysis and informed decision-making (De Camargo et al., 2023). This shift has also spurred the development of applications designed to visualize and interpret large datasets, responding to the increasing demand for data analytics within the sector (Idoje et al., 2021).

A meta-analysis identified water quality as a critical component in the aquaculture production chain. Key factors such as dissolved oxygen, which is essential for the survival of aquatic organisms, as well as temperature, pH, total dissolved solids (TDS), chemical factors, and other indicators for husbandry, ensure healthy growth and control fish mortality (Yu et al., 2022). One of the current concerns in this field is the management of the cultural environment due to its impact on production. In this context, Ferreira et al. (2022) highlighted the IoT as one of the most significant technologies for advancing the sector, particularly for monitoring and control purposes. Similarly, Antonucci and Costa (2020) provided a bibliometric review and structured term map analysis of research articles on precision aquaculture published between 1991 and 2019. Their findings identified key research trends related to environmental monitoring tools, sensor networks (e.g., wireless and long-range systems), data interpretation tools, and decision-making processes aimed at enhancing production efficiency and improving the quality of fishery products.

Given this scenario, this study aims to review the current state of use and adoption of technologies in aquaculture. Envisioning IoT as a valuable tool for experimentation and knowledge generation can foster greater confidence within the industry and promote widespread adoption, particularly benefiting small-scale producers and contributing to meeting the growing demand for fish products. The objective of this systematic literature review is to identify the best practices, architectural frameworks, employed components, and the main challenges related to the implementation of IoT technologies in the fish farming sector. The review follows a structured methodology: first, formulating research questions; second, searching specialized academic databases using key descriptors; third, defining inclusion and exclusion criteria; fourth, assessing the relevance and quality of the selected contributions; and finally, conducting an analysis and synthesis of the literature to determine the current state of research in this field.

2 Systematic approach

2.1 Review methodology

For this study, a systematic literature exploration approach proposed by Nawaz et al. (2022) was adopted, which outlines five structured phases: (1) definition of research questions, (2) search for information, (3) identification of inclusion and exclusion criteria, (4) evaluation of the selection process, and (5) data extraction and synthesis. See Figure 1.

First, defining the research questions:

- 1 How can 4.0 technologies contribute to the sustainable transformation of the aquaculture sector?
- 2 What are the architecture and the components that the IoT uses the most for water quality monitoring in aquaculture?



FIGURE 1
Phases of the literature review.

3 What challenges arise in the implementation of IoT technologies within the aquaculture sector?

In the information search phase, an automated query using key descriptors in English was conducted for each of the formulated research questions. See [Table 1](#).

The Dimensions database was selected as the search engine due to its widespread use and free accessibility. The evaluation period covered the years 2018 to 2022 and included only open-access articles published in various journals. The total search queries yielded 1,235 publications: 318 for research question Q1, 767 for Q2, and 150 for Q3. See a detailed distribution of the publications by year in [Table 2](#).

A total of 968 records obtained from the query in BibTeX format were imported into the Rayyan.ai tool ([Ouzzani et al., 2016](#)). This process identified 278 duplicates, of which 147 were eliminated, resulting in an initial set of 821 articles.

The inclusion criteria required full access to the article content and focused primarily on aquaculture and water quality monitoring in environments such as fish farms or ponds, specifically involving IoT technology, architectures and their components, network protocols, cloud platforms, benefits, and challenges. The exclusion criteria eliminated articles that were non-English, outside the evaluation period, unpublished in journals, or related to technologies other than the IoT.

In the evaluation phase, articles were analyzed for relevance by examining their titles, abstracts, and keywords to determine whether they met the inclusion criteria. A total of 87 full-text articles were retrieved: 17 for Q1, 35 for Q2, and 35 for Q3. Of these, 49 were excluded because they did not directly address the research questions. Consequently, 38 articles were selected as the most relevant for the literature review.

Finally, the researchers conducted data extraction and synthesis for each selected article. They extracted relevant information to provide answers to the research questions using a standardized template that contained attributes such as year of publication, source, country of origin, author, title, and specific data related to keywords aligned with the research objectives.

[Figure 2](#) presents the results of the information search phase (see [Table 2](#)), illustrating the annual publication output retrieved from the Dimensions database for the period 2018–2022, based on each predefined search string. The data revealed a notable increase in the volume of publications over the evaluated years, indicating increased academic attention to the topics addressed in this study.

Another notable result of the evaluation phase was the identification of the 26 countries that contribute most to the bibliographic corpus, as shown in [Figure 3](#). This figure corresponds to search string number 1 and reflects global interest in the use and adoption of 4.0 technologies to design solutions that enable competitiveness and sustainability in the aquaculture sector. Notably,

TABLE 1 Search strings for the research questions.

Research questions	Search strings
Q1	("4.0 Technologies" OR "4.0 industry") AND ("aquaculture" OR "fish farm") AND "literature review"
Q2	("Internet of Things" OR "IoT") AND "monitoring" AND ("fish farming" OR "aquaculture") and "water quality"
Q3	"Challenges" and ("Internet of Things" OR "IoT") and ("aquaculture" OR "fish farm")

TABLE 2 Number of publications by search strings.

Year	Q1	Q2	Q3
2018	10	47	11
2019	22	69	14
2020	56	137	22
2021	82	221	47
2022	148	293	56

Asia emerged as the leading continent, with China contributing 10 publications, followed by India with six and Taiwan with five. The United States contributed four publications, while Bangladesh and Colombia each accounted for three. Countries with two contributions included Brazil, France, Indonesia, Italy, the United Kingdom, and Thailand. In addition, the following countries each contributed one publication: Australia, Ethiopia, Canada, Ireland, North Macedonia, Malaysia, Mexico, Norway, the Netherlands, Pakistan, Panama, Portugal, Singapore, and Ukraine. These findings suggest that the identified countries have demonstrated significant development and application of IoT technologies within the aquaculture sector.

[Table 3](#) presents a list of 21 journals, together with their quartile rankings according to SCImago, reflecting the primary sources related to computer science and agriculture used in this study.

The literature review enabled the formulation of responses to the research questions as follows:

2.2 The internet of things in the sustainable transformation of the aquaculture sector

The literature review indicates that the current focus on the application of 4.0 technologies plays a critical role in advancing precision agriculture. These technologies rely on networks of interconnected sensors deployed within farming environments to

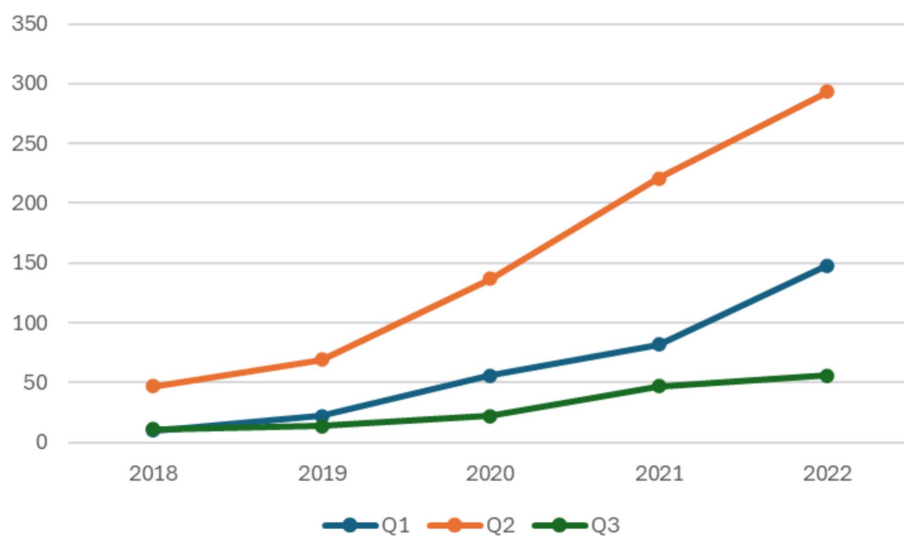


FIGURE 2
Number of publications per year pertinent to each research question.

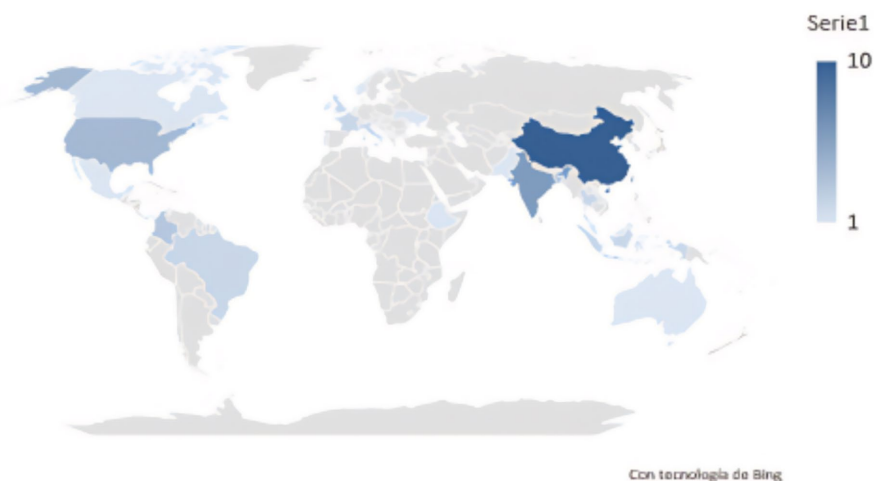


FIGURE 3
Origin of publications according to dimensions.

monitor, analyze, interpret, and support decision-making processes (O'Donncha and Grant, 2020). Applications of Industry 4.0 technologies in agriculture can be classified into five main categories: (a) climate and microclimate (e.g., environmental conditions, humidity, precipitation, wind), characterized by real-time capture of these variables with high temporal frequency (Rebaudo et al., 2023); (b) livestock (e.g., disease detection, location tracking, parasite control, milk quality monitoring); (c) crops (e.g., growth monitoring, disease identification, water requirements); (d) soil (e.g., carbon content, moisture levels); and (e) water (e.g., flow rate, levels, nutrient concentration, physicochemical parameters). Routine farming activities, when combined with continuous and real-time monitoring of species welfare and product quality, significantly enhance the assessment and management of health and productivity. In the context of a growing global population, the integration of agri-food systems

with Industry 4.0 technologies offers key features for everyday livestock practices. These technologies offer valuable tools for improving efficiency, reducing environmental impact, and supporting the long-term sustainable development of the agricultural sector (Morrone et al., 2022).

In addition, Liberata and Sinha (2020) conducted a critical review of key contributions and research studies on Environmental Monitoring Systems, encompassing areas such as air quality, water quality, radiation pollution, and agricultural systems. Their review highlights the application of the IoT and AI in monitoring and analyzing water pollution within agricultural contexts.

In fish farming, water can quickly lose its ability to support vital functions such as reproduction, waste excretion, growth, and feeding within fishponds. Therefore, understanding and carefully managing fish needs, water quality parameters, and the factors

TABLE 3 List sources according to dimensions.

Journal	Number of articles	Quartile SCImago
Sensors	15	Q1
Computers and Electronics in Agriculture	2	Q1
Applied Sciences	2	Q2
International Journal of Mathematical, Engineering and Management Sciences	2	Q2
Aquaculture and Fisheries	1	Q1
Aquaculture International	1	Q1
Aquaculture Reports	1	Q1
Journal of the World Aquaculture Society	1	Q1
Methods in Ecology and Evolution	1	Q1
PLoS One	1	Q1
Science of The Total Environment	1	Q1
Sustainability	1	Q1
Information Processing in Agriculture	1	Q1
Computers and Electrical Engineering	1	Q1
IEEE Access	1	Q1
Smart Agricultural Technology	1	Q1
Journal of Agriculture and Food Research	1	Q1
Microprocessors and Microsystem	1	Q2
Environ Monit Assess	1	Q2
Data in Brief	1	Q3
International Journal of Electrical and Computer Engineering	1	Q3

influencing them are essential. When filling fishponds, farmers must consider both the chemical and physical properties of the water. The IoT shows significant potential for monitoring the water quality necessary for optimal fish production. [Manoj et al. \(2022\)](#) reviewed several studies conducted between 2011 and 2020, highlighting key advancements in the qualitative and quantitative assessment of water quality parameters. Their work also examines common IoT architectures and devices employed in fish farming and proposes a roadmap to guide future developments in this domain.

On the other hand, one of the most challenging aspects of aquaculture is the mitigation of abiotic and biotic stress caused by various chemical and microbial contaminants in the water. These stressors significantly affect crop health and reduce production. The IoT offers the capability to accurately detect both biotic and abiotic stressors in a short time, providing reliable monitoring that can enhance confidence in managing these contaminants ([Chakraborty and Krishnani, 2022](#)).

In addition, the rapid advancement of sensors, computer vision, and acoustic technologies has enabled sophisticated methods for counting aquaculture species, an important task for accurately estimating fish populations ([Li et al., 2021](#)). However, this area presents a broad field for research due to the diverse factors involved. Furthermore, integrating IoT technology with blockchain enables

seamless incorporation into supply chains and customer-facing applications such as CRM systems.

This integration allows consumers to access reliable information about suppliers and products, while companies can reduce costs and expand market opportunities. Moreover, government agencies can use these technologies to enforce quality control and ensure safe operating conditions for aquatic products ([Jæger and Mishra, 2020](#)).

2.3 Architecture and components used in water quality monitoring in the aquaculture sector

The IoT and wireless sensor networks (WSNs) are rapidly evolving to meet the growing demand for application scenarios such as automation and remote process control, enabling efficient data transmission, processing, and security. These devices are also used to enhance the efficiency of existing networks and create new opportunities for industrial process optimization ([Majid et al., 2022](#)). Consequently, specialized architecture is necessary to support these functionalities. In this regard, [Shi et al. \(2019\)](#) proposed a four-layer architecture consisting of the following components:

- Perception layer:** This layer consists of physical devices such as sensors, control equipment, and data acquisition terminals. The sensing devices collect environmental data, including oxygen (O₂), pH, temperature (Temp), turbidity (NTU), salinity (S), and nitrite ([Skarga-Bandurova et al., 2020](#)). These sensors can interface with hardware controllers such as Arduino, NodeMCU, and Raspberry Pi ([Raju and Vijayaraghavan, 2020](#)). Control equipment includes aerators (oxygen cones), feeders, pump valves, and other aquaculture machinery ([Wang et al., 2021](#)).
- Network layer:** This layer constitutes the IoT infrastructure and includes a network of various communication technologies and the internet. Transmission media can be wired or wireless, such as Wi-Fi, Zigbee, Bluetooth, LoRa, and NB-IoT ([Bayih et al., 2022](#)). It is responsible not only for transmitting data collected by the perception layer to the upper layers but also for relaying control commands from the application layer back to the devices in the perception layer, enabling appropriate actions and simplifying new service development and device deployment.
- Common platform layer:** This layer handles data storage and management and runs various models for prediction and early warning during the production processes. It primarily relies on cloud computing platforms capable of hosting Big Data applications, ML algorithms, and other core processing technologies.
- Application layer:** This layer includes platforms for environmental monitoring and control, early warning systems, disease management, and agricultural product safety traceability. These applications enhance production efficiency while reducing time and costs. [Table 4](#) presents implementations of IoT solutions for water quality monitoring within the sector of interest in this study.

TABLE 4 IoT solution implementations.

Author and year	Variables					Hardware		
	Temp	pH	NTU	O ₂	S	Arduino	Raspberry Pi	Other
Sousa et al. (2019)	X	X	X	X			X	
Arafat et al. (2020)	X	X	X			X		
Alselek et al. (2022)	X	X		X				X
Olmedo and Smith (2021)	X	X	X	X		X		
Abdullah et al. (2021)	X	X		X				X
Bates et al. (2021)	X				X			
Islam et al. (2022)	X	X	X			X		
Kinar and Brinkmann (2022)	X		X			X		
Medina et al. (2022)	X	X		X		X		
Lu et al. (2022)	X			X	X	X		
Sarwar and Iqbal (2022)	X	X		X		X		
Putra et al. (2022)		X						X
Lin et al. (2021)	X	X		X				
Chiu et al. (2022)	X	X	X	X		X		

Water quality monitoring systems have incorporated different architectures and components. Islam et al. (2022) proposed an IoT framework for real-time monitoring of aquatic environments using Arduino and sensors. Similarly, Arafat et al. (2020) presented a monitoring system based on experimental data collected directly from a fishpond, using respective sensors to measure parameters, such as temperature, pH, and turbidity. The dataset included records from different water levels to enable a more effective analysis of the aquatic environment, and ML regression models were applied to predict future water conditions. Chiu et al. (2022) also used the same parameters, which incorporate actuators such as heaters, water pumps, stirrers, and smart feeders. In addition, they employed an underwater camera for real-time monitoring of fish growth and feeding behavior. An Arduino Mega 2,560 microcontroller, integrated with a Wi-Fi module, manages the system, which controls the sensors and actuators and transmits data to a cloud server.

Similarly, in aquaponics systems, the integration of IoT technology enables the monitoring of dissolved oxygen levels in water bodies, providing essential data for modeling system dynamics using techniques such as fuzzy neural networks. These models are vital for predicting and managing fluctuations in oxygen levels, which are crucial for maintaining the stability and overall health of the system (Ren et al., 2018).

2.4 Challenges in the implementation of the IoT in the fish farming sector

Globally, aquaculture faces serious problems related to environmental pollution, disease, and limited product traceability. Although it has traditionally been one of the slowest sectors to adopt new technologies, there is now growing interest in recent innovations, which presents an opportunity for more sustainable and profitable production (Yue and Shen, 2022).

Some authors have identified a range of challenges related to the implementation of 4.0 technologies in the small-scale sector. For example, Antony et al. (2020) highlight issues such as limited access to measurement devices (including component availability and device design), poor connectivity affecting data transmission, difficulties in data storage and analysis, inadequate feedback mechanisms and automation processes, and challenges related to project structure and support, including sustainable business models. These challenges warrant careful attention from both academia and the research community.

Majid et al. (2022) also highlight additional challenges, including energy consumption, connectivity issues, and the complexities of long-distance deployment. The use of low-cost sensors presents additional challenges, particularly the need for calibration tailored to specific deployment conditions. Another significant aspect is the low quality of sensory data, which often requires preprocessing through appropriate filters and signal processing techniques to enhance its suitability for environmental monitoring tasks. In addition, the performance of WSNs is constrained by factors such as limited battery capacity, computing power, and communication bandwidth (Shi et al., 2018).

On the other hand, although the numerous achievements in the application of the IoT in smart agriculture have significantly enhanced agricultural practices, several limitations persist. These include concerns related to data security and privacy, as well as resistance from stakeholders due to a lack of cultural readiness to embrace IoT innovations. Furthermore, the high cost of deployment and the complexity involved in integrating the IoT with other computing technologies and networks continue to present substantial challenges (Idoje et al., 2021).

Another important challenge lies in the integration of collected data into algorithms capable of predicting water quality by estimating the factors that influence its variation. The integration of IoT technologies and the development of technologies such as 5G will drive the transition toward fully connected aquaculture

systems, which will enhance the quality of data acquisition and enable more effective control of the production environment (Barrios-Ulloa et al., 2021). Therefore, the path to complete automation in aquaculture involves a sequence of steps: measurement, analysis, identification, and action. This progression has the potential to revolutionize the sector through interconnected systems for both aeration and health monitoring, addressing the needs of a growing global population in a more balanced and responsible manner.

The technologies proposed to address the challenges related to insufficient data collection, limited information sharing, and lack of automation among stakeholders in aquaculture farms are the Semantic Web and AI. These technologies offer new capabilities for collecting and organizing data in an interoperable format, which can then be processed and applied to monitoring and decision-making. Another proposed solution involves the integration of a back-end processing center with an ML-based water quality prediction model, suitable for farms of various scales (Ouyang et al., 2021). In addition, Haq and Member (2022) suggest the use of deep learning (DL) techniques, including convolutional neural networks (CNNs) and gated recurrent unit models, to improve the accuracy of water quality prediction.

Beyond conventional water quality sensors, aquaculture is increasingly harnessing optical, acoustic, and biological sensors to monitor currents, particulates, pathogens, and harmful algal blooms. In addition, the application of drone-acquired imagery, encompassing direct videography of fish and satellite remote sensing, is expanding within the industry (Wei et al., 2020). The advancement of DL algorithms to analyze these images and extract essential information about fish behavior, tracking, and health constitutes a significant area of ongoing research (Mei et al., 2022).

Table 5 presents a list of current challenges associated with the implementation of IoT in the aquaculture sector.

3 Conclusion

The study has several key strengths that reinforce the validity and usefulness of its findings. First, the adoption of a structured five-phase methodology ensures a systematic and rigorous approach. This methodology includes the formulation of precise research questions, a search for specific information, and the application of clear inclusion and exclusion criteria, which guarantee the relevance and quality of the selected sources. This process enabled an in-depth analysis and the

effective identification of the key factors that impact production, as well as the essential architectural components for water quality control in aquaculture. A second significant strength lies in its ability to offer a comprehensive overview of the applications, architecture, and challenges of the IoT in the aquaculture sector. By synthesizing the existing literature, the review not only confirms that this technology represents a considerable opportunity for growth but also accurately outlines the current challenges that prevent more effective implementation.

However, it is essential to acknowledge the inherent limitations that may have influenced the scope of this study. First, the search for information included only one database, which likely restricted access to high-impact articles and significant contributions indexed to other specialized databases. This limitation may have resulted in less comprehensive coverage of the global research landscape. Second, access restrictions to proprietary journals prevented the consultation of important contributions that could have enriched the analysis. Decisively, limiting the search exclusively to indexed journals may have led to the exclusion of a considerable volume of relevant, high-quality scientific output published in other formats. This notably includes contributions presented at major conferences, which often set trends and offer highly relevant and timely findings in a field as dynamic as Industry 4.0 technologies in aquaculture.

Although the focus was on applications for water quality control, the study also had a significant interest in smart aquaculture. This interest stems from the use of Artificial Intelligence (AI) to address challenges related to data collection and sharing, as well as the automation of processes among different actors in the supply chain. AI enables the development of predictive models based on historical and real-time data to anticipate fish growth and farm performance. This allows aquaculturists to better plan their operations by adjusting stocking density, scheduling harvests, and targeting specific markets. The authors suggest directing future research resulting from this study toward diagnostic analyses of the use of camera systems for monitoring, robotic systems and automation for repetitive tasks, and modern strategies for detecting species growth. Alternatively, future studies could aim to identify the contributions of implementing Industry 4.0 technologies to sustainability, resilience, and competitiveness indicators in small-and medium-sized aquaculture enterprises in Latin America.

Moreover, the analysis conducted in this study reveals that, although there is considerable global interest in the adoption of IoT and Industry 4.0 technologies in general, significant challenges persist that require effective research-based solutions to support this sector

TABLE 5 Challenges of IoT implementation in aquaculture production.

Author and year	Challenges					
	Cost	Connectivity	Consumption Energy	Maintenance of sensors	Linking farmers	Integration with other technologies
Shi et al. (2018)		X	X			
Antony et al. (2020)	X	X	X			
Bates et al. (2021)			X	X		
Majid et al. (2022)	X	X	X	X		
Wang et al. (2021)	X	X		X		X
Medina et al. (2022)	X					
Lu et al. (2022)	X		X		X	X

urgently. These challenges include high implementation costs, limited connectivity, high energy consumption, and poor planning for sensor maintenance. The current outlook of the sector, in light of these challenges, indicates that many fish farms are excluded from adopting and using these new technologies, placing them at a competitive disadvantage in securing a meaningful share of the global market and ensuring long-term sustainability. In line with this, it is important to highlight that, in most cases, companies with limited access to IoT technology also face economic constraints and a reduced capacity to invest in improving production processes. Therefore, it is essential for stakeholders to develop strategies for strengthening collaboration and cooperation, focusing joint efforts on overcoming challenges and successfully entering the global market—an environment currently marked by tensions in international trade resulting from conflicts and trade wars.

Irrevocably, the modernization of the aquaculture sector, supported by using the IoT, arises as a priority need, especially in developing countries and emerging economies. These regions require the strengthening of robust economic units that foster an inclusive and sustainable ecosystem within rural communities. At the same time, by supporting the development of this sector, governments can reduce dependence on imported aquaculture products subject to high tariffs, which increase prices and limit access to nutritionally valuable products, particularly for vulnerable populations, thereby jeopardizing their food security. Overcoming these challenges to improve the sector's competitiveness will enable governments to effectively adapt and respond to global food crises, thereby contributing to the achievement of food sovereignty.

Author contributions

MR: Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. CG: Formal analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. EA: Formal analysis, Investigation, Resources, Writing – review & editing. CR: Formal analysis, Investigation, Resources, Writing – review & editing. JR: Formal analysis, Investigation, Methodology, Writing – review & editing. AL-P: Conceptualization, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the Ministry of Science, Technology, and Innovation (MinCiencias) of Colombia under the contract No. 009-2024, call for proposals 943-2023.

Acknowledgments

The authors would like to thank Asociación Agropecuaria Grassian—Granja Acuaponica San Sebastian—Grassian, Universidad del Sinu—Elias Bechara Zainum Seccional Cartagena, and Ministerio de Ciencia, Tecnología e Innovación (Minciencias) of Colombia for funding the project under contract 009-2024, call 943-2023: “*Convocatoria fomento a la innovación y desarrollo tecnológico para contribuir a resolver los retos asociados con el derecho a la alimentación—“Senainnova” por un campo productivo y sostenible*”.

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