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Technological Advancements in Aquaculture Water Quality Monitoring: A Brief Review

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ABSTRACT

Aquaculture has emerged as one of the rapidly growing industries, creating employment opportunities and providing nutrition to a vast majority of the population. With the increase in population, the demand for aquaculture has also increased. As per the **National Fisheries Policy (2020)** report, the total fisheries potential of India has been estimated at 22.31 million metric tons contributing 1.07% to the national GDP. The usage of information and communication technology in aquaculture helps maintain the quality standards of fish farms which leads to high production, and thus optimizing the cost for the farmers. In India, the practice rate of technology-based farming is very low mainly due to high implementation costs. However, numerous devices are currently being developed to provide cost-effective systems to manage data and water quality. This review aimed to provide an overview of the current aquaculture practices based upon the usage of advanced technology depicting their contribution to aquaculture.

INTRODUCTION

Aquaculture is the world's fastest-growing food-producing sector. It already provides 50% of all fish consumed globally, and is expected to become the primary source of fish by 2030. Currently, India ranks second after China in aquaculture whereas in fisheries production, it is the 3rd. In 2014, the country's estimated fish production was around 4.88 million tonnes which provided a national GDP of 1.07% and an agricultural GDP of 5.30% **(Ayyappan, 2014; Dubey *et al*., 2018; Ngasotter *et al*., 2020)**. On the other hand, according to the **National Fisheries Policy (2020)** report, the estimated total fisheries potential of India is 22.31 million metric tons, contributing 1.07% to the overall national GDP. Despite its growth, some issues such as disease, low production, high input cost, and environmental challenges are affecting aquaculture **(National Fisheries Policy, 2020)**. Water quality decides whether an aquaculture project will succeed or fail as all the activities of fishes are completely dependent on it as they need to breathe, feed, grow, expel wastes, maintain a salt balance, reproduce and thrive in water. It is important to understand the physical and chemical properties of water as it is vital to the success of aquaculture to increase production and to avoid risks of environmental damage **(Swann, 1997)**. The continuous monitoring of water should be done so that unfavorable conditions can be predicted in the early stage and can be mitigated **(Ferreira *et al*., 2011)**.

Fish farming can be carried out in three ways, i.e., extensive, intensive, and semi-intensive (Fig. 1). Extensive fish farming or traditional fish farming is commonly associated with fish farming in medium- to large-sized ponds or water bodies, where the fish output is based on the water's inherent productivity, which is only little or moderately boosted. Inputs from outside sources are restricted, and the amount of fish produced per unit area is poor. The level of control over the production components is kept low, but the labor return is high. Intensive fish farming, on the other hand, means that a large number of fish are produced per unit of rearing area. Production parameters including feed, water quality, and the quality of stocked fingerlings are all regulated to improve the culture's production circumstances. In intensive aquaculture, the risk of disease also increased more due to stocking. Apart from these two types of fish farming, some people practice semi-intensive fish farming, which refers to techniques that combine aspects of both types.

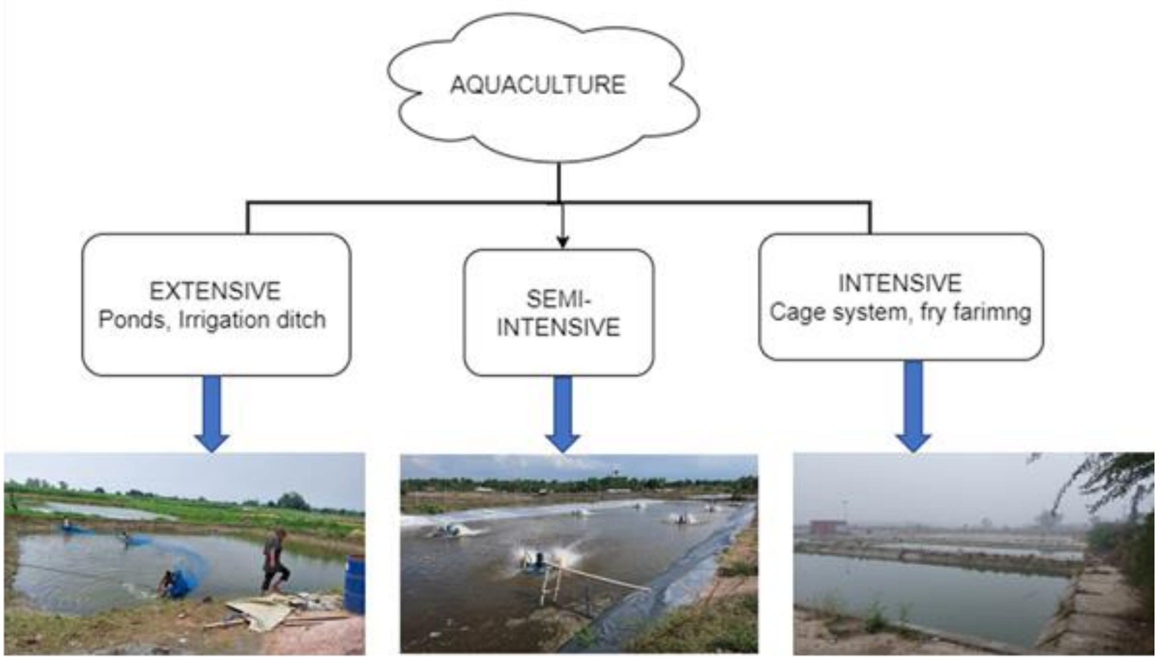

Fig. 1. Types of aquaculture techniques

It can be seen that all methods need extra efforts by farmers to make fish farming their primary economic source. Fish production can be influenced by a variety of factors, including temperature, transparency, turbidity, carbon dioxide, pH, alkalinity, hardness, ammonia, nitrite, nitrate, primary productivity, biochemical oxygen demand (BOD), and plankton population **(Verma *et al*., 2022)**.

Waterbodies especially near industrial areas get easily contaminated. Due to a lack of environmental regulations and industrialization, these parameters get changed affecting the productivity of the water body. Water temperature mainly affects the growth of aquatic organisms. Massive changes in water temperature result in poor growth. Fish are cold-blooded, yet their body temperature changes in reaction to their environment. This affects their metabolism, physiology, and production. As temperature rises, the microbiota's metabolic activity and respiration rate increase to meet the increased oxygen demand. It also lowers oxygen solubility and raises ammonia levels in water. Ammonia is a byproduct of fish protein metabolism and bacterial decomposition of organic substances, including food waste, faeces, dead plankton, and sewage. The unionized form of ammonia (NH_3) is highly hazardous, but the ionized form (NH_4^+) is not. Both forms are collectively referred to as "total ammonia". A biological process called nitrification can convert toxic ammonia to harmless nitrates. High densities of fish in ponds can increase the risk of ammonia toxicity. Ammonia levels above 0.02ppm can damage gills, destroy mucous-producing membranes, and have "sub-lethal" effects such as reduced growth, poor feed conversion, and disease resistance even at lower concentrations. It can also cause osmoregulatory imbalance and kidney failure. However, toxic levels of nitrite, an intermediate form of ammonia, have been observed in fish ponds causing brown-blood disease **(Bhatnagar *et al*., 2013)**.

As phosphorus is a necessary plant nutrient, adding it to water will encourage the growth of plants, including algae. According to **Stone and Thomforde (2004)**, a phosphate level of 0.06mg L-1 is desirable for fish culture. Dissolved gases, particularly nitrogen, are typically measured in terms of "percent saturation." Supersaturation occurs when the amount of gas in the water exceeds its typical capacity at a specific temperature. Gas supersaturation levels above 110 percent are often considered harmful. Gas bubble illness is a sign of gas oversaturation. The symptoms of gas bubble sickness differ. Bubbles can reach the heart or brain of fish, causing them to die without an obvious evidence. Other symptoms may include bubbles beneath the epidermis, in the eyes, or between the fin rays. To treat gas bubble disease, aeration should be adequate to reduce gas concentrations to saturation or below **(Swann, 1997)**.

The acidity or basicity of water is determined by the concentration of hydrogen ions (H^+) in it. The pH scale, which goes from 1 to 14, is used to determine how acidic a substance is. Values below 7 are regarded as acidic, while values above 7 as basic. A value of 7 is neutral, neither acidic nor basic. According to **Swann (1997)**, for fish culture, a pH range of 6.5 to 9.0, is usually appropriate. Low pH results in acidic water due to the leaching of metals from rocks and sediments occur. This results in the fatality of fish as these further accumulate in organs. Numerous data points show that fish metal accumulation rates are directly impacted by water acidification. When data on metal concentrations in fish from different lakes are compared, it can be seen that fish from acidified lakes have significantly higher concentrations of cadmium and lead, but not zinc

(Grieb *et al*., 1990; Wiener *et al*., 1990; Haines & Brumbaugh, 1994; Horwitz *et al.*, 1995). Copper accumulation is likewise greater at lower pH values **(Cogun & Kargin, 2004)**. In summary, water acidification may either directly or indirectly affect fish bioaccumulation of metals by altering the solubility of metal compounds or by damaging epithelia that become more permeable to metals whereas in some cases competitive uptake of H^+ ions may prevent fish bioaccumulation of metals **(Jezierska & Witeska, 2006)**.

With the increasing trend of intensive aquaculture, threat of disease has increased, which should be tracked and regularly monitored. All of these measures necessitate strong procedures and investments, raising production costs.

Many methods are used to monitor water quality, but they either serve purposes other than aquaculture or lack integration with online communication systems. The conventional method (Fig. 2) in which first the samples are collected from the site and are then transferred to the laboratory for the test. These are time-consuming and also there are chances of large variation as work may vary from person to person based on their previous experience **(Zhu *et al.*, 2010)**. As the reliability of technology increased, the focus on implementing it in every field has also increased.

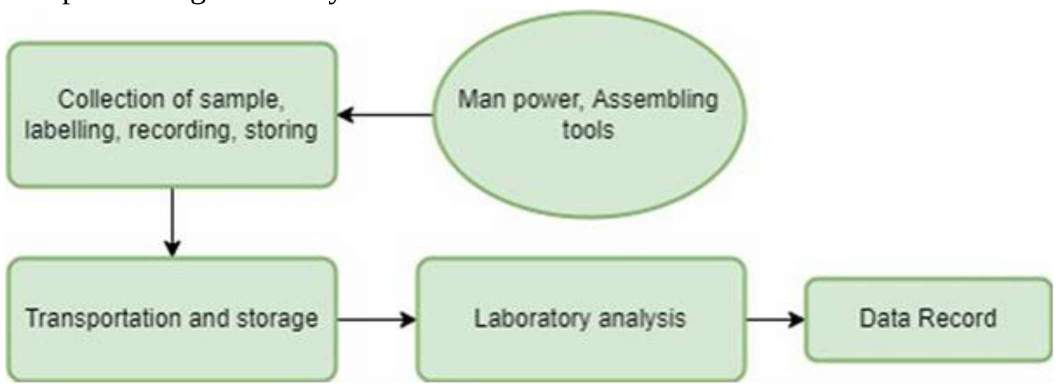

Fig. 1. Conventional water quality assessment procedures for aquaculture monitoring

Fish farming has the least exposure to technology due to which its productivity suffers and therefore the involvement of technology is necessary for this area. Technology in aquaculture can help increase productivity. With the help of technology, farmers can easily keep track of their work with fewer efforts **(Powell *et al.*, 2017)**. For the monitoring of water quality in aquaculture, there are countless methods proposed in this area. But not all are equally beneficial, some are time taking while some are costly or not conveniently available to the small farmers. Water quality monitoring systems based on wireless communication technologies (WCTs) and the Internet of Things (IoT) have been widely studied around the world **(Danh *et al.*, 2020)**. In this review, we focused on some of the technologies which are currently used in the aquaculture field to monitor water quality.

Sensors and wireless technology for aquaculture monitoring

Physical (electrical conductivity, salinity, total dissolved solids, turbidity, temperature, color, and taste and odor) and chemical water (pH, acidity, alkalinity, hardness, chlorine, and dissolved oxygen) quality parameters are some of the important variables which play a pivotal role in affecting the water quality. Previously, several technologies were used for water quality monitoring but they were not connected with online monitoring systems. Traditionally, the water quality of fish farms was tested on-site using handheld sensors (Fig. 3) on a regular basis. Regardless of the species of fish, the aforementioned physical requirements are typically necessary to sustain optimal levels of fish growth.

Fig. 2. Different types of handheld sensors for testing aquaculture physiochemical parameters. **(A)** Conductivity/TDS meter, **(B)** Digital nephlo-turbidity meter, **(C)** pH meter, and **(D)** Scientific thermometer

While handheld tools or sensors can offer onsite measurement by staff during office hours, variations in one of the essential water parameters beyond a safe threshold can occur outside of office hours, undetected by employees. When a terrible condition persists, it might have negative consequences such as low growth, undiagnosed disease symptoms, or strange fish behavior. However, real-time monitoring based on wireless sensor networks (WSNs) makes the monitoring much more convenient and accurate **(Zhang *et al.*, 2013)**. WSNs are a type of network that consists of interconnected sensor nodes that communicate wirelessly in order to collect data about the environment.

The use of technology in monitoring has been introduced/ picked in the last decade. A remote wireless system was introduced by **Zhu *et al*. (2010)** using wireless communication technology for online water quality monitoring in intensive fish culture. This system monitors dissolved oxygen (DO), pH, salinity and temperature in real-time and gave more than 95.2% correct data. It can also give early warning signals on notable changes in values. The proposed system's application is however currently limited due to its rigorous operational requirements and expensive maintenance costs.

Water quality monitoring systems for aquaculture based on wireless sensor networks have sensors that monitor pH, water level, DO, and temperature. This system senses these parameters in real-time and also send the data directly to the users. It is user friendly, as it can monitor the data at any time on demand. This along with wireless sensors equipped with decision-making control software which make use of expert knowledge stored in the database can achieve better results (**Zhang & Wang, 2011)**. In a further development, a wireless system to monitor some basic and important parameters of water quality such as DO, pH, conductivity and temperature was developed with a wireless communication interface that communicates to the remote station located around 1km area of the interested site. The system was found to withstand harsh environmental conditions but was found to be not economically feasible **(Vaddadi *et al.*, 2012)**. On the other hand, the ZigBee wireless sensor network-based water monitoring system can store the sensor values and compare them with the reference limits. It monitors all the common parameters temperature, pressure, DO and can send an alert via SMS or E-mail to the holder if the values exceed the reference limits **(Espinosa-Faller & Rendón-Rodríguez, 2012)**. Recently, **Chen *et al.* (2022)** in Taiwan developed a robotic arm performing automatic measurements and maintenance procedures. The Arduino Mega 2560 microcontroller was used to transmit the water quality dataset over a LoRaWAN network.

Internet of Things (IoT) solving economic issues

The internet has evolved enormously over the last four decades, from a small private network of a few nodes to a global public network with billions of nodes. The term "Internet of Things" (IoT) was coined by **Ashton (1999)** to describe the trend toward networked "things" that collect data through sensing and execute calculations on the sensor data. IoT is a broad word with no clear meaning, but it refers to a wide range of "things," from everyday objects to complicated biosensors, that are capable of sensing/ actuation, communicating to the internet, and processing. The IoT is the concept of connecting any device to the internet and other connected gadgets (Fig. 4). The IoT is a huge network of networked objects and people that collect and share data on how they are used and how they interact with their surroundings.

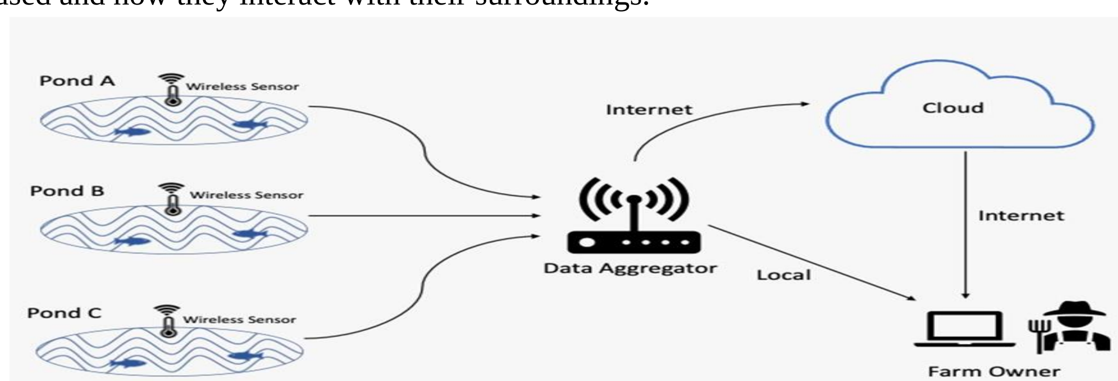

Fig. 4. Implementation of wireless IoT communication technology in fish farm management

In implementing the different systems for ensuring the quality of fish farms, the main barrier is high cost. Small farmers in comparison to large farmers lack the advanced technology system for to check the progress of their work. Also hiring people to work on daily water quality checks is not possible for small farmers **(Teja *et al.*, 2020)**. The aquaculture IoT systems are economically very useful. The farms which are using IoT systems are more productive than those that are not using them; as IoT systems decrease the labor cost and are less time taking. **Sung *et al*. (2014)** proposed a wireless remote monitoring system using the wireless sensor network with the ZigBee which monitored the temperature, pH and DO on aquaculture farms. The system enables real-time monitoring with the aid of mobile devices and remote platforms. The system collects the data with the date and time and sends the information to the internet from which the information can be accessed easily and helps control the situations of farms.

A cost-effective and multiparameter monitoring system was developed which provides real-time data on aquaculture water quality based on a wireless sensor network **(Luo *et al.*, 2015)**. The system uses lithium cells and solar cells for the power supply and has sensors for DO, ammonia, nitrogen, temperature and pH. However, the system lacked automatic control of pH, ammonia, nitrogen and needed further improvement. **Powell *et al.* (2017)** gave a scalable, versatile, more economical remote monitoring system with the concept of IoT and proposed its future work with artificial intelligence (AI) in the system for more advantageous results. The system was designed to monitor the temperature, pH, DO and stored the data provided by the sensors in a database easily accessible from anywhere through the mobile app. With the increase in developing better products, **Gao *et al.* (2019)** developed an IoT-based intelligent fish farming and tracking control system. The system not only performed monitoring of the parameters of water quality but also was able to keep track of breeding as well as the sale of fish. The system includes six types of sensor monitors for simultaneous measurements of temperature, conductivity, water level, pH, water turbidity and DO. The collected data from the sensors get stored in a database system. The system also included a product tracking system in which by scanning the QR code of the product, one could trace all the information regarding the product such as its geographical location, transportation and all the farming process to the consumer. This system is a highly useful improvised approach, as the system could prove very effective in providing the trustworthy quality of aquatic products.

Boonsong *et al*. (2018) suggested a wireless sensor network (WSN) in an IoT platform for a smart water quality monitoring (SWQM) system of aquaculture ponds. Temperature, the amount of dissolved oxygen in water, and potential hydrogen (pH) values were the key variables examined in this study. The router gateway transmits the data that is monitored with the suggested SWQM device to an operator via a cloud Internet platform. To accomplish real-time monitoring, the operator can use the tracked information data on a smart device.

In another recent report, a low-cost sensor to monitor pH, temperature, water level and humidity was developed **(Teja *et al.* 2020)**, which stores data at regular intervals of time in the cloud and is accessible by the user through the Blynk application in their mobile. The system can send alerts to the user and can take important actions automatically.

Smart aquaculture

There is a consistent requirement for intensified aquaculture production to meet the food demand of the growing global population. Given the diversity in aquaculture farming in terms of methods, practices, and facilities, human labor alone is insufficient and new intelligent aquaculture models are greatly needed **(Wang *et al.*, 2021)**. The emergence of the IoT, big data, artificial intelligence, 5G networks, cloud computing, and robot technologies makes intelligent aquaculture possible **(Li & Li, 2020)**. Intelligent aquaculture can increase resource usage efficiency and sustainability in a variety of ways. It can also lower labor costs, boost production, and improve aquatic product quality. Other problems, such as high capital and energy costs, should, however, be addressed in order to develop intelligent aquaculture **(Li & Li, 2020)**. Recently, keeping in view the concept of smart aquaculture, **Sivakumar and Ramya (2021)** proposed a system named as low-cost real-time monitoring system (LCRTMS). This system with IoT monitors pH, water temperature, DO and ammonia. Sensors collect the data and send it to the cloud over the internet which can easily be accessed and the further process can be done with minimal human interaction. **Akhter *et al.* (2021)** proposed a low cost, low power water quality monitoring system with IoT based sensors to access the data in real-time. The system has multi-sensors to monitor various parameters which include temperature, pH, DO, calcium, magnesium, nitrate and phosphate. The proposed system can be easily operated to keep track of the water quality regularly. Additionally, the users can get expert advice from anywhere anytime they need.

Lin *et al*. (2021) proposed a novel wireless multi-sensor system that monitors the water quality of freshwater aquaculture by combining the temperature, pH, DO, and EC sensors with an ESP 32 Wi-Fi module. The ThingSpeak IoT platform presented the temperature, pH, DO, EC, and salinity levels of the water along with an easy-to-use visualization provided by the ThingView APP. The suggested wireless multi-sensor IoT system is capable of monitoring freshwater aquaculture water quality with adequate accuracy, dependable confidence, and good tolerance.

In terms of smart aquaculture, the suggested wire-free multi-sensor IoT system has several advantages over multiple single sensors, including easier setup and maintenance, better cost-effectiveness, and sufficient accuracy and reliability with pre-calibration even for commercialized sensor devices. Additionally, the system allows for simultaneous on-site monitoring of multiple sensing parameters in close proximity to an aquatic cultivation field over weeks or even months, as well as a significantly cost-effective improvement in labor costs.

Another system named E-Sensor AQUA system is a water quality monitoring IoT based system useful in measuring the pH, salinity, temperature, oxidation-reduction level, and DO in real-time. The system also has an automatic sensor probe cleaning mechanism which reduces the high maintenance cost and makes use of technology affordable to small farmers. All of these systems were designed to meet the demand for multimode sensors by establishing data communication and a feedback loop to initiate actions. To ensure data reliability, a reliable sensor network should have optimal sampling algorithms continuing with the aim of smart aquaculture. In most cases, IoT solutions in aquaculture employ a local server to store the massive amounts of data collected in an Excel file or database. As a result, the Internet infrastructure is put under a lot of strain. Cloud computing supports IoT by providing a virtual storage location and conduit for the massive amounts of data and applications that need to be stored and retrieved. It not only improves the approaches' efficiency and scalability, but it also enables improved collaboration between engineers working from different locations **(Gupta *et al.*, 2022)**.

The latest example of an intelligent fish farm is the one designed by **Chiu *et al.* (2022)** to meet the requirements of a California Bass fish pond in Taiwan. Their primary objective is to streamline the manpower needed for fish pond maintenance through the utilization of automated devices and Artificial Intelligence of Things (AIoT). The proposed intelligent fish pond incorporates various sensors, including dissolved oxygen, pH, turbidity, and temperature sensors. Devices such as the heater, water pump, and pH sensor are shielded by a wind-proofing device during fish pond operation. Others, like the food-feeding device, turbidity sensor, dissolved oxygen sensor, temperature sensor, and agitator, interact directly with the fish pond without wind-proofing protection. A micro-controller, specifically the Arduino Mega2560 with an integrated Wi-Fi module, orchestrates the heater, water pump, limit switch, all sensors, food feeding device, IPCAM, motor, and agitator for real-time surveillance **(Chiu *et al.* 2022)**. All data are stored in a cloud server, where they are collected and analyzed using big data and AI techniques. Important features are then employed to generate deductions on the system's productivity through machine learning, including deep learning. Mobile applications are also available for remote surveillance and control **(Chiu *et al.*, 2022)**. Data from the California Bass fish pond system were collected over fifty-two weeks. Following statistical verification and analysis, the optimized prototype achieved a high R2 value of 0.94, with an average square value of 0.0015 **(Chiu *et al.*, 2022)**. These values demonstrate the feasibility of the proposed model to achieve the desired output. The researchers believe that this intelligent fish pond model can offer significant benefits to fish farmers worldwide, including reduced food residue, enhanced fish growth, minimized fish mortality, and improved feed conversion ratio.

Currently, biosensors, which use electronic technology to evaluate the functions of living organisms, are being actively researched and developed. Biosensors use electrodes and optical devices to detect small changes and convert them into electric signals, allowing for quick and accurate measurement of specific substances. Biosensors with high sensitivity and specificity are being developed for assessing fish health **(Endo *et al*., 2019)**. Physiological stress in fish causes a primary response of hormone concentration changes, such as cortisol and catecholamine, followed by a secondary response of blood glucose changes due to stress hormone metabolic activation. The stress response is influenced by physical factors like flow velocity, temperature, and contact, chemical factors like ammonia, nitrous acid, and poisons, and behavioral factors like predation threats, fish social activities, and territorial behavior **(Bonga, 1997)**. While various factors such as high ammonia levels, can cause chemical stress. **Endo *et al.* (2006)** created a needle-type biosensor system that consists of an optical oxygen fiber probe with a ruthenium complex, an immobilized enzyme membrane, and a hollow needle-type container (18-gauge needle) for the quick and easy measurement of glucose concentrations in fish blood. This sensor inserted into the caudal vein of the fish, measure blood glucose concentrations by measuring changes in the concentration of dissolved oxygen. This procedure involves removing the fish from the water tank using a net in order to draw blood samples for each measurement, which could stress the fish unnecessarily. Additionally, fish glucose concentrations vary in response to stress, making real-time measurement extremely desirable.

Endo *et al.* (2010) devised an innovative wireless biosensor system which is inserted in the eyeball interstitial sclera fluid (EISF), the interstitial fluid inside the outer membrane of the fish eyeball to track fish glucose levels in response to these issues. The output current value of the sensor is transmitted to land via radio waves, allowing the glucose concentration to be tracked in real time by connecting it to a waterproof wireless potentiostat. This kind of fish sensor system is novel and can measure blood glucose levels in real time even when test fish are swimming around freely. In addition, to be able to assess stress responses using a more intuitive output, **Wu *et al.* (2019)** developed a method of visual output an optical communication type biosensor system to indicate the level of stress which can measure blood glucose concentration.

Precision farming via technological innovation

With the challenges mentioned for aquaculture production, various strategies must be identified and implemented. The availability of unmanned vehicles outfitted with overhead cameras, sensors, and computational capability for site surveillance also are well known. To achieve more precise fish farming, more autonomous and continuous monitoring is required, which can give more reliable decision support and decrease reliance on manual labor and subjective evaluations to improve worker safety and welfare. Precision aquaculture is defined as a network of heterogeneous and interconnected sensors used to monitor, analyse, interpret, and support farm operations **(Teja *et al.*, 2020)**. It applies control engineering principles in fish production to improve farm monitoring, control, and allow documentation of biological processes and biomass monitoring **(Føre *et al.*, 2018)**.

Because precision agriculture is developing so well, the suggested IoT platform by **Lin *et al.* (2021)** offers a biotechnology development that is both flexible and expandable, enabling the simultaneous monitoring of a wide range of cultivation parameters in agriculture while maintaining transparency and quality control throughout the entire process. Measurement robustness and user-friendliness will be improved upon by taking consideration of the ageing and maintenance needs of aquatic sensors. Because of its availability and affordability, unmanned vehicles or aircraft are one of the developing technologies widely used in agriculture and aquaculture for fish management and monitoring. Drones are now being used to capture environmental data and fish behavior at aquaculture sites for monitoring **(Chang *et al.*, 2021; de Lima *et al.*, 2021)**.

Autonomous underwater vehicles (AUVs) or remotely operated underwater vehicles (ROVs) are waterproof and submersible in water because they are outfitted with cameras to capture images and videos as well as sensors to collect data on water quality such as water temperature, depth level, chemical, biological, and physical properties **(Paull *et al.*, 2014; Sward *et al.*, 2019; Yuan *et al.*, 2023)**. Because AUVs are submerged underwater, one of the problems is high navigational precision, communication, and localization due to the inability to rely on radio communications and global positioning systems. Yet, one of the solutions proposed to address these issues is geophysical navigation **(Ubina *et al.*, 2022)**. An augmented reality (AR) plus cloud system has recently been developed to enhance the query and gathering of *in-situ* water quality data **(Xi *et al*., 2019; Yue & Shen, 2022)**. AR is also expected to make significant contributions to fish farm management, such as water quality management, remote collaboration, and boardroom discussion. However, the affordability of such systems is always an important consideration when using this technology on small fish farms. In addition, the aquaculture industry benefits from the development of simple and cost-effective AR software. Testing is being done on a 3D-printed water sensor system that can identify pH, temperature, and oxygen content **(Banna *et al*., 2017)**. The cost of manufacturing and equipment, the need for post-processing, and the scarcity of materials suitable for use in water and other environments are some of the obstacles to 3D printing's adoption in aquaculture. Collaboration among aquaculture scientists, fish farmers, engineers, and software developers is necessary to address these issues and create cost-effective products for the aquaculture sector by integrating 3D printing technology into products and business models. The aquaculture sector could undergo a revolution, thanks to IoT and big data solutions, which would increase productivity, sustainability, and profitability while also enhancing safety and simplifying risk management. Consequently, it greatly increases the interconnectedness of supply chains and processing systems. Applying IoT technologies to remote marine aquaculture sites is still a practical challenge, though, as data collected from sensors located far from the main fish farm must be sent elsewhere in the world **(Yue & Shen, 2022)**.

Issues such as high labor cost, time consuming and susceptibility to errors due to traditional methods may get possibly solved through the integration of computer technologies like data analytics, the IoT, and AI. Nevertheless, there are issues with performance, interpretability, and data variability with the deep learning systems available today. To address these limitations, **Arepalli and Naik (2024)** proposed a comprehensive framework that incorporates IoT-based data collection and data segregation techniques to improve the precision of aquaculture water contamination classification. The study introduced the Ordinary Differential Equation Gated Recurrent Unit (AODEGRU), a novel attention-based model to assure robust categorization. Accurate classification of water contamination and water quality evaluation is enabled by utilizing advanced device sensors enabled real-time data collection for temperature, pH, dissolved oxygen, and nitrate concentration. This AODEGRU model computes a water contamination index using fish-specific permissible ranges, which makes it easier to accurately separate data into contaminated and non-contaminated classes as this model is trained with labelled, high-quality data. Even so, it has limitations in terms of adjusting to aquaculture's dynamic character. However, the study further focused more on factors in future research like scalability, long-term maintenance, and flexibility to changing circumstances.

Although sensors make things smooth, using them comes up with many challenges. Sensors must be low-maintenance, low-cost, battery-efficient, robust, waterproof, non-metallic, biofouling-resistant, and non-toxic to organisms. If possible, it is recommended to avoid using optical sensors. It is important to study the threshold values of fishes' hearing abilities and the effects of magnetic fields caused by sensors **(Parra *et al.*, 2018)**. In addition, concerns about data security and privacy arise when IoT is implemented in numerous businesses, and aquaculture is no exception. The aquaculture sector contains a lot of sensitive data, including trade secrets and patented techniques, which makes protecting these data an essential issue **(Assaf *et al*., 2024)**. In general, aquaculture has benefited from IoT-based technologies since it makes real-time management easier while enhancing sensor corrosion resistance and incorporating data fusion to improve decision-making require improvements **(Abdullah *et al*., 2024)**.

CONCLUSION

It is evident from the data that aquaculture is a rapidly growing and in-demand sector of farming. Until now, most farmers have relied on traditional fish farming methods, which have resulted in low efficiency and yield. These challenges can be overcome through the use of technology, enabling farmers to monitor and manage water quality while saving labor costs and time, ultimately improving fish production. To meet growing demand, aquaculture must adopt these technologies at the same, or even a faster, pace. The evolution of sensors and IoT implementation in aquaculture has elevated fish farming to new levels, but it has not penetrated the industry as expected. There are significant gaps between the availability of revolutionary and disruptive technologies and their actual usage in aquaculture. Barriers such as high costs, low-level implementation, limited customization (according to farmers' needs), and the complexity of understanding these technologies prevent widespread adoption among Indian fish farmers. IoT in aquaculture offers new hopes for increased productivity, but it requires improvement. Moving forward, the focus should be on developing technology that is easy to understand, simple to implement, efficient, and affordable—features that will drive large-scale adoption among farmers.

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CONFLICTS OF INTEREST

All the authors declare no conflict of interest.

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