

# Aquaculture and Computers—Innovations and Applications

V. Basil Hans<sup>1,\*</sup>

## Abstract

*Aquaculture, the cultivation of aquatic organisms for commercial purposes, has grown significantly over the past few decades due to the increasing global demand for seafood. The integration of computer technologies into aquaculture has revolutionized the industry, enabling more efficient management of resources, improved production processes, and enhanced sustainability. Computers and digital systems facilitate real-time monitoring of water quality, fish health, and feeding systems, while data analytics and artificial intelligence (AI) aid in optimizing growth conditions, reducing waste, and predicting disease outbreaks. Automation technologies, such as robotics and IoT (Internet of Things) sensors, also support the precision farming of aquatic species, leading to higher yields and reduced environmental impacts. This article explores the role of computer technologies in modern aquaculture, emphasizing their contributions to improving operational efficiency, promoting sustainability, and ensuring food security in an increasingly resource-constrained world.*

**Keywords:** Sensors, food security, commercial species, farmed fish area, unfavorable predators

## INTRODUCTION

Fishery products play a central role in the strategies for food security and nutrition in Asia, Africa, and the Pacific Islands. Many consumers in these areas rely almost entirely on fish for sustenance, yet the supply is becoming scarcer. Because of this, it is becoming more and more difficult for these regions to meet their food security and nutrition requirements. The world's fish production in 2018 was about 179 million tons, of which 44% came from marine capture fisheries and 56% from inland fisheries. Total fish farm production contributed about 34% of the gross production. It is estimated that the harbors cultivated about 31% of the total fish production, while the oceans of the world yield about 22 million tons of fish from capture [1].

Fisheries also provide tens of millions of individuals, primarily in the developing world, with job opportunities. However, the COVID-19 pandemic has affected fishermen, and the disruptions in fishing operations have resulted in a major disturbance to the world's aquatic market supply chain. The growth rates in world fish production and trade have slowed since 2016, while simultaneously the prices of most wild commercial species have seen a significant decrease. Therefore, more effort is urgently required to

promote aquaculture and cultivation-based fisheries as environmentally sustainable providers of food security and nutrition. The cultivation of aquatic organisms for the first time has surpassed beef, which is about the same as the production of pigs.

## LITERATURE REVIEW

Technology in aquaculture has expanded at a phenomenal rate during the past 50 to 100 years. Based on both this past progress and the present technological advances being made in our society, it is reasonable to expect aqua culturists to profit

**\*Author for Correspondence**  
V. Basil Hans  
E-mail: [vhans2011@gmail.com](mailto:vhans2011@gmail.com)

<sup>1</sup>Research Professor, Department of Management and Commerce, Srinivas University, Mangaluru, Karnataka, India

Received Date: March 04, 2025  
Accepted Date: April 10, 2025  
Published Date: April 16, 2025

**Citation:** V. Basil Hans. Aquaculture and Computers—Innovations and Applications. Journal of Computer Technology & Applications. 2025; 16(2): 70–85p.

from the rapid technological advances being made in both hardware and biological systems. These advances will result as spinoffs from medicine, from analytical chemistry, and most importantly, from the evolution of new consumer products such as auto-focus cameras, electronic watches, and microprocessor-monitored automobiles. We can expect to use economical, reliable instrumentation capable of environmental monitoring for predictive purposes and instrumentation that will contain alarm and control circuits. Genetic engineering will result in biological organisms that produce hormones, drugs, and other biological materials as well as detoxify pollutants on demand. When we as aqua culturists identify the need for a product, that product will be developed [2].

The world wild fish stocks are being depleted in an ever-increasing speed. Aquaculture is the only way to ensure sufficient seafood for the world. Conventional aquaculture can be traced back to 4000 years in China and has been very successful in the past three decades. However, aquaculture has faced serious challenges, including only a few improved species, labor-intensiveness, environmental pollution, diseases and lack of traceability of products. Aquaculture needs disruptive technologies to increase fish production. Novel and disruptive technologies, including genome editing, artificial intelligence, offshore farming, recirculating aquaculture systems, alternative proteins and oils to replace fish meals and fish oils, oral vaccination, blockchain for marketing and internet of things, may provide solutions for sustainable and profitable aquaculture [3].

### **HISTORICAL DEVELOPMENT OF AQUACULTURE AND COMPUTERS**

The unique intersection of aquaculture and computers signals a broad scope, covering almost all aspects of aquaculture: medicine (veterinary studies, fish disease, and prevention and control of fish diseases), farming techniques (fish feed, nursery farming, breeding and seedling production, fish capture, and transportation of farmed fish), law (aquatic product quality and safety, aquatic ecological environment, and aquaculture), water quality control of farmed fish, and equipment (aerator, water pump, monitoring instrument of water environment, and configuration instrument for farmed fish). Intelligent ear tags or radio-frequency identification (RFID) ear tags and a computer network system can be used to realize the automatic recognition and statistics of farmed fish number, make the farmed fish get out of the water, when automatically identified farmed fish number is greater than a preset value of the farmed fish number in the cage. A computer control system can be used to obtain and record various parameter information of farmed fish and aquatic products in real time, so as to satisfy the traceability requirements for the quality and safety of farmed fish and aquatic products. The qualified statistic method to recognize fish number is provided to ensure the safe and reliable operation of the multi-application ear tag system. On realization of video capture technology, fish identification technology, and transmission technology based on wireless communication network, a farmed fish number recognition and statistics system is developed [3]. On installation of farmed area of ear tag transceiver to the feed barge and feed storage tank, a wireless data transmission device is designed to implement data communication between the feed barge and the feed storage tank. The farmed fish are uniquely tagged with an ear tag, so the farmed fish can be identified in all seasons/cages without the need for artificial conduction. Documentary information of good traceability of the production process of farmed fish is presented, satisfying the requirements of farmed fish traceability. On the automatic identification and control of multi-function intellectual vision for the aquaculture cage insulator are proposed. On receiving the video information of the farmed fish area provided by the video camera and the video information of the farmed fish number of four non-overlapping sections analyzed by the farmed fish number recognition and statistical algorithm, the presence of fish leakage is detected on the farmed fish number and is less than or equal to 50% of the underwater pixel number, the detected signal boxed fish real number detection error rate is less than 4%, and the operation success rate of the multi-application ear tag system greater than 98%.

### **KEY CONCEPTS IN AQUACULTURE AND COMPUTERS**

Successful fish farm management is intrinsically connected to the ability to maintain optimal living conditions for aquatic life. In the controlled setting of an aquaculture site, a litany of careful decisions

needs to be made on a daily basis to ensure the best care for inhabitants of the farm: fish, crustaceans, mollusks, and algae. The environmental conditions in which these animals thrive must be carefully regulated. Aquatic health should be regularly assessed, and any illness caught in its early stages to prevent further spreading. Liabilities such as waste products, potential contaminants, and unfavorable predators are keenly looked after. With fish farms growing ever larger in scale, often exceeding systems even traditional to agriculture, technology stands to aid an industry that is only increasing in importance. The latest innovation comes in the form of computing helping agriculture meet the sea. On the most basic level, physical adjustments and manual maintenance achieve the desired environmental conditions. Filling a farm with tanks of water hosts is the easy part. The hard part has always been maintaining the optimal conditions; in this context, fish health and productivity are directly related to environmental conditions. Temperature, for example, has an exceptional influence on many aspects of aquatic life. During winter or seasonal changes, water temperature can fluctuate quite rapidly, thereby negatively affecting the overall wellbeing of the fish in the farm. Small rises have also been shown to directly aid parasites and other aquatic pests. This makes regulating this aspect of aquafeed a top priority [3]. Ensuring an optimal amount of dissolved oxygen is paramount—without it, fish suffocate, do not grow, exert themselves less, and are more susceptible to disease. In contrast, too much can negatively impact fish growth [4]. In reproducing the natural facades which growing conditions are most favorable, other aspects come into focus: water purity, oxygenation, feeding regimes, and selective cultivar constraint. For the species of fish farmed, this comparison is never more important than when considering pH levels—a factor heavily dependent on animal variety. It is also the most difficult to regulate, as there are many variables that influence it, from animal excretions to intermittent water treatment. This can lead to conditions rapidly slipping out of hand. The first idea of an environmental control system for an aquaculture site is born. Such systems work closely with a large quantity of equipment, sensors, and a neural network, which effectively understand the complex natural of aquafeeds. This paper introduces a pioneering environmental control system using cutting-edge technology, facilitating aquafeed while optimizing resource utilization. The system comes in face of internet of things (IoT) devices, being far more affordable to maintain, adaptable, and scalable than traditional means. Configured in a wireless sensor network that interacts with both animal behavior and the environment, this system constitutes a direct decision support mechanism based in a bespoke neural network. This network is unlike any current system on the market—it lacks the hysteresis or other control elements needed when processing an order. Instead, it decides to take action solely based on the readings and overall operation policy. Although to effectively process, this control network only makes simple recommendations for certain physical processes like oxygenation and temperature, leaving other tasks to the network of auxiliary machine learning algorithms.

## **AQUACULTURE MONITORING AND CONTROL SYSTEMS**

With the continuous increase of the global population and the decrease of marine biological resources, fish farming has become one of the major aquaculture models to meet fish demand. The global fish trade has increased significantly, and it is accompanied by the rapid growth of fish farming. To produce enough seafood for everyone, the world's food production must double by 2050. Developing countries need to triple food production in this period. On the other hand, aquaculture has grown approximately twice as fast as the world average rate over the past three decades, and farmed fish production overtook wild capture production for human consumption in 2014. Given the decrease in capture fisheries' production, the rise in aquaculture has been central to growth in the fisheries and aquaculture sector. Aquaculture generates millions of jobs all over the world and contributes to alleviate poverty and hunger, generates economic growth and improves nutrition. Over the past 60 years, aquaculture has become one of the fast growing and industrialized food producing sectors in the world. Aquaculture is currently considered the fastest growing sector of food production; it represents 47% of total fish supply intended for human consumption.

### **Sensors and Data Collection**

Nowadays, the aquaculture production is continuously increasing due to the concern of healthy nutrition. The aquaculture environment needs to be continuously monitored to prevent large losses and

increase production. To maintain the aquaculture environment in optimal conditions, the pH, dissolved oxygen, temperature, total ammonia nitrogen, nitrite, etc. are carefully monitored. However, this monitoring process is hard and time-consuming if the aquaculture pond is far from the fisherman's residence. Therefore, proper technology to continuously monitor the aquaculture environment is necessary [5].

Nowadays, aquaculture technology is increasingly introduced in the production mode. One of the methods is to use the IoT technology in aquaculture. Wireless sensor networks (WSN) are widely used in aquaculture. This is because WSNs allow farmers to monitor growing conditions in real time and to keep data accurate, more complete and more useful as a production hydroponics system. After that, the results of this research will be useful in aquaculture circulating systems with the addition of more complete sensors. The strengths of this research lie in the unity of the development of the aquaculture monitoring system circulating by combining the ZigBee JN5139 module with the development of the prototype web-based monitoring system, which has a pH sensitivity, total dissolved solids (TDS), and flow sensors and allows being simple to use for easy moving. The results of the study provide knowledge about the implementation of the ZigBee WSN prototype of JN5139 module for the aquaculture circulating system application.

The commercially available installations for real-time water parameter measurements in aquaculture systems use data from industrial, rigorous, and expensive sensors. The aim of this work was, in the first place, to design, build and test a small, low-cost and easy-to-use set of sensors for measuring the water quality in aquaculture tanks. These sensors were designed for monitoring the main parameters that affect the survival and growth of fish (pH, dissolved oxygen, conductivity and water temperature) and were rugged and completely waterproof, so they can be deployed in-situ, during the regular operation of the fish farm tanks. A dedicated data acquisition system allows recording the output of the sensors at a given sampling rate.

### **Automation and Robotics**

Aquaculture is facing many challenges, including climate change, diseases, water quality, waste discharge and environmental damage. In order to alleviate the negative impact on aquaculture production, it is very important to take urgent action to embrace the application of modern computer technologies in aquaculture, turning traditional fish farms into intelligent fish farms [3]. They are supported by modern information technology such as comprehensive perception, intelligent processing, intelligent navigation and automatic control technology to realize unmanned production, environmental information monitoring, optimization control and precise operation. Robots, unmanned vehicles, unmanned boats and robotic fish will play an important role in intelligent fish farm.

In order to improve the productivity, efficiency, and sustainability of fish farms, a variety of robots and other front-tier technologies are exploited and integrated such as cybersecurity, IoT, big data, cloud computing, mobile app, drones, cameras, biometrics, 3D printed cage and blockchain. Using the limb mechanism, the first treading robot has been developed for aquaculture that can walk and run in a mudflat or estuary, capturing the geolocation and monitoring the biology and environment around aquaculture sites. Online intelligence service system and deep learning-based fish recognition system are developed for remote diagnosis, detection, prediction and intelligent infrastructure. Using the data-driven deep learning approach, fish production prediction system is developed. At the same time, algorithms for automatic identification, detection, counting, grading and treatment of fish diseases are developed. By using the camera surveillance network, the suspicious objects can be automatically detected and the warning message is sent to the fish farm owner or fish farm member on time.

### **Remote Sensing Technologies**

Modern advanced remote sensing technology is the use of various advanced high-tech equipment and materials, and the integration of the latest technologies in marine science fields such as optics, acoustics, and microwaves. The marine resources are rich, and intelligent technology with advanced sensitivity

will be gradually applied to the future fish farm. Equipped with various advanced high-tech equipment such as temperature, salinity, and turbidity to install a sensor-based intelligent environmental control system, which will greatly increase the operational efficiency of the fish farm. It is equipped with various advanced high-tech equipment such as machine vision to set up an automatic inspection process of fish diseases, which can do a thorough examination every day, 24 hours a day.

The mission of aquaculture has always been to find ways to match population growth and the sustainable use of seafood resources. The realization of this vision requires substantial progress in understanding developmental aquaculture in natural and constructed aquatic systems and the development/implementation of sustainable aquaculture technologies. The national implementation plan elaborates on this vision, stating that the goal of this initiative is to help the nation meet its growing marine fish needs, both economically and sustainably. To achieve the goal, a coalition of aquaculture research institutions and industry has been formed to strengthen the technological, sustainable methods that promote fish survival and health, to significantly increase yield and water resource use efficiency. Further consultation with technologists and resource managers is required on the application of visualization technologies to move the fishery Annual Work Plan (AWP) to a fully developed status.

### **COMPUTER MODELING AND SIMULATION IN AQUACULTURE**

Aquaculture is currently the fastest-growing food-producing sector in the world. A necessary condition for the efficient and sustainable management of this sector is a sound understanding of the physical, chemical, and biological processes that are involved in aquaculture production systems. Associated with this is the need for the development of suitable instruments, numerical models and experimentation techniques that enable the characterization of these processes. There are two recognized approaches in this modeling process. The first is the use of an existing body of knowledge on the subject and physical measurements. In the course of time, these models have usually been developed by the scientist/engineer essentially on the basis of empirical data. A more general approach that has been applied to engineering devices, chemical processes among others is to make use of the well-established system of conservation laws [6]. This latter type of modeling uses mathematical techniques based upon fundamental physical principles to describe the phenomenon in question. This paper presents results from a study in which there was an attempt to develop a model for the flow in and around a net pen situated in a rectangular channel. The model was developed with the help of a computer program. The model was validated by comparison to the results from both laboratory tanks and from the field. With this validated model, various aspects of the flow in the cage were examined. In particular, the interaction between the cage and netting was investigated and methods to define the flow characteristics of the pen were examined. The insights which this model provides may facilitate the future development and use of cage systems.

#### **Biological Models**

Today's economy is facing necessary sustainable development issues. Aware of that, it is possible to give as example an important economic sector which is, nevertheless, along the years, an important one for economy development, and particularly for countries that have coastlines or internal bodies of water, such as lakes or ponds: the aquaculture. In this industry, in contrast to marine and open water fisheries, most of the environmental parameters must to be controlled to optimize fish health and productivity. And it is therefore preferable to embrace the notion of smart or intelligent fish farm, which explicitly considers the need for efficient monitoring, adaptation and control rooted in online data mining [3]. But it is possible to do more automation and integration of software and hardware in the process. Given the novelty and potential economic impact of this kind of software, and the fact that it can be applied to virtually any production process in aquaculture (from the arrival of eggs to the packing of fish and even in the case of waste and fish feed), an integrated aquaculture software has been developed. The globalization and interconnected world of nowadays give the chance for this integrated aquaculture software to be cloud-based and enterprise-resource software-based, that is, to work at any time at any place through the Internet, and be supported by an integrated database that can manage aquaculture data

---

as well as customer's data. Completely designed and programmed, this aquaculture software is an "all-in-one" solution to enhance and optimize the aquaculture industry. A wide range of biological models is predefined in the software, which can be run to predict growth, mortality, feed requirements or make any kind of mathematical prediction based on historical data and other factors.

### **Environmental Models**

Aquaculture is one of the most important food sources on the planet. It is the fastest growing food sector worldwide, contributing to the livelihoods of millions of people. With the rise of fish farming worldwide, technological advances in the field are required. Various models, machine learning models in particular, have achieved success in resources and input optimization, leading to increased production. In addition, physical models can both support system management and identify the structure of fish habitats. In this sense, an increasing trend of fish farms entering the era of digitized agriculture. Other benefits of incorporating computers into fish farming include resource optimization, waste reduction, problem anticipation, structure identification, and ease of access.

The majority of work conducted focus on enhancements to fish cages themselves. Research has shown that the incorporation of certain shaped devices to cages results in the reduction of water pressure; such methods are deemed to lower material costs and reduce the risk of anchor displacement. Also, device-based methods to reduce waste near fish farms have been developed. By utilizing drone swarms, a fish school's movement behavior could be successfully regulated, limiting it from near farm sites. Other drones are used to pick up waste accumulating near farms. High-quality remote control systems typically require a yearly fee. Given such limitations associated with available technologies and tools, developing models to better understand and coordinate fish productivity with fish farm structures introduces an interesting scientific problem. Modeling could be a great tool in deciding where and how to perform changes to fish farms in order to manage them more efficiently and in a more predictable manner.

### **Economic Models**

Innovations in computer technology are among the most prominent and rapidly evolving effects in the aquaculture industry. The use of computer technology and technical applications have increased the efficiency and profitability of aquaculture businesses, ranging from global positioning system (GPS)-controlled growing efforts to more elaborate models predicting the social consequences of aquaculture development. This section offers practical examples of how computers and software are used in a broad spectrum of industry sectors, as well as provides augmented analysis on the communication skills required of computer users and programmers. The scope encompasses geographic information system, econometric models, farm simulation software, and communication technologies.

The rising importance of computers and technology in aquacultural applications has spawned new developments in statistical and econometric approaches. Developments have included streamlined methodologies when evaluating aquaculture profitability, cost-effectiveness potential, and productivity of workforce. Modeling, interrelated with network communications systems, computer-genetic control applications, GPS positioning, is contributing to increased difficulty and versatility of modern farming scenarios. The availability and exploitation of rapid up-to-date data are also important to make better marketing decisions. The assimilate impact of technological developments in aquaculture and computer use is expected to widen to a greater extent in forthcoming years [7].

## **ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN AQUACULTURE**

The excessive human intervention makes the production efficiency unstable, labor costs high, and difficult to form a working method with good continuity and scientific basis. As the marine catch decreases, the demand for farm-raised fish and shellfish is expected to increase. In order to increase the economic benefits of farming operations, equipment has been used to control the culture. The field not only increases the survival rate and quality of products but also shortens the fully open to the harvest

period to reduce the impact of squid-infested diseases and unusual weather. Equipment used in aquaculture production has evolved from passive devices to intelligent devices that control the timing and dosage of water changes and feeding. Since people follow traditional working methods and are influenced by artificial factors such as subjective mood and skill level, it is possible to measure and record various environmental karats and culture processes of the farm through electronic data collectors and sensors that are capable of analyzing past operation data. Scientists use different disciplines to research and collect data. After the statistical model is built, it is analyzed and predicted, so as to derive the preferred culture method. This not only reduces the impact of artificial factors but also provides a scientific basis for future operations. In order to achieve the above functions, the device must be able to improve hardware in addition to the programmable microprocessor. Since electronic hardware components have the ability to transform the world into data with numbers, the data collected by these components can reflect the basic situation of farming practices. These components that affect the culture are used to design the data acquisition system, so that scientists can easily grasp and make decisions. Farmers can purchase measurement kits to arrange a similar environment or method for sampling, and then use the user-written computer plug and principal component analysis software to analyze the data to obtain the results [3].

### **Applications in Feed Optimization**

Many different paradigms have been proposed for model predictive control (MPC), and the choice is application-dependent. For instance, in environmental systems optimization upstream control is considered. Recently, MPC has received increased interest and it has been more energetically applied in industrial processes. The prototype systems have included concentration greater or lesser than the desired value to be controlled. In precision aquaculture, the primary goal is to maximize biomass production while minimizing production costs. This can be achieved by optimizing factors that have a strong influence on fish growth; the feeding rate, temperature, and oxygen levels.

The candidate MPC formulations evaluate three schemes for fish growth reference tracking based on receding horizon approaches. The first MPC formulation tracks a desired fish growth trajectory while penalizing the feed ration, temperature, and oxygen levels. The second MPC optimization strategy directly penalizes feed conversion ratio, while minimizing the actual growth state's deviation from the given reference growth trajectory. The third MPC formulation includes a trade-off between the growth rate trajectory tracking and another growth-related parameter. The two static growth models tested yield an off-parabolic growth trajectory. Optimal feed rations solved from the two growth models tested produce unrealistically high feed conversion ratios. Systems incorporating mechanistic modeling are more relevant for efficient management of aquaculture. Performance is relevant to growth-model choice and either of the two mechanistic models favors one formulation. Viable methodology for cage-based aquaculture is continuous monitoring of fish collective swimming behavior to determine biomass estimates and hence derive optimal feeding strategies. As an example, the commercially important gilthead sea bream becomes quite sensitive to cannibalism once it reaches a certain size, and therefore the farming strategy must carefully address this issue.

### **Disease Detection and Management**

Nowadays, aquatic products play a vital role in the global food supply chain. Especially for Asian-Pacific, millions of households depend on it for protein intake. Fish diseases are a key concern for human health throughout the supply chain, from production to commercialization. There is similarity in how disease origins multiply, be it viral, bacterial, or parasitic. The evolution of diseases is usually rapid, adopting innovative bio-strategies; which cause difficulties for their management and eradication. In the sea-cages, including the bays, disease outbursts spread rapidly; traditional methods involve the excessive use of medicine, which sometimes goes to the point of poisoning the water.

Both mature and complementary species are studied. It is proposed to place stressed fish in a sensitive tank and observe them. It is crucial to use the technology of counting the amounts sensorily; also, when the camera cannot see the fish. This herd behavior is especially used by the camera's machine learning

in determining sick fish. It is feasible to use a genetically modified sensor-fish controlled by a drone algorithm that can sense the stress-specific water quality and provide early intervention. These sensors are distributed according to the prospective locations of bio-encrusted cages and are stationary on the ocean bed in a typical survey of disease history. Every morning, they record parameters to machine learning predictive algorithms. Similarly, the aerostatics perform the same functions for cages in ponds. Automatic calibration or drainage system activation occurs when it is detected that the disease is increasing accordingly.

### **Stocking Density Optimization**

The rapid growth of the aquaculture industry and the decline of natural resources have prompted the study of optimal fish harvesting density. Pond farming is the most ancient form of aquaculture in the world. The most common fish harvested using pond farming is carp, which is often grown with other freshwater fish. Similar to all closed systems aquaculture production, pond aquaculture is a system that requires monitoring and controlling the environment surrounding the fish in ponds. Fish toxicity or stress can be caused by high stocking densities, poor water quality, or other unfavorable environmental conditions. Fish can be stressed by factors such as handling, grading, transport, and changes in rearing conditions. Stress usually induces an increase in plasma cortisol levels in fish. Fish under stress conditions, like transport, can activate primary physiological responses, such as an increase in plasma cortisol level in fish. To assess the condition of fish exposed to organic pollution, the concentration and toxic effects of certain metals are tested. In fish which are exposed to pollution, osmoregulation disturbances and changes in ion balance are often seen, and the levels of chloride in plasma may be highly altered. Here, the depletion of the antioxidant defense system in fish and the accumulation of reactive oxygen species can lead to cell damage. Many free radical scavenging enzymes are present in organisms, such as superoxide dismutase. Under stress conditions, the activity of these enzymes in the gills and liver of carp was found to change. In addition, the concentration of glutathione in fish tissue changed under stress conditions. Therefore, plasma cortisol levels and sodium oxide dismutase (SOD) activity were used to evaluate the impact of stress and stocking density in fish.

### **BIG DATA ANALYTICS IN AQUACULTURE**

Aquaculture is a common means of production worldwide, but compared with traditional agriculture, fish ponds, and other aquaculture equipment have the characteristics of being on or under water, which makes it difficult to acquire more real-time and effective aquaculture monitoring data. The monitoring images obtained by an aquatic fish farm camera have problems such as large blurry areas and low focuses and missing critical fish disease objects. The uneven lighting of the image background causes a high error rate in abnormal behavior monitoring based on image analysis. Underwater monitors are designed as tens of thousands of small lattice detectors that consist of micro-mesh printed traces on the dielectric substrate. Underwater monitor camera production is rainproof and anti-corrosive. The differential active electrode can filter out the specific scalar background noise, such as the power supply noise, to enhance the detection sensitivity of the underwater camera.

The instability of network transmission brings difficulties to the back-end data processing and intelligent data analysis. Aquaculture big data technology has increasingly become a hot spot, and the combination of aquaculture and big data technology can effectively support all aspects of aquaculture. This adds the broad band part where annoying noise is coupled between the lines. If the camera looks close to the fish farmer, the fish farmer will be disturbed. The agricultural field of the same era is taking fast steps in aquaculture and horticultural aspects. This study designs an adaptive variable phrase delay with a phase offset of  $15^\circ$  to  $45^\circ$  between the high-pass filter and the low-pass filter. Gain permits and impulse hurdles are used to design a wild dispersive loopback compensator.

### **INTERNET OF THINGS IN AQUACULTURE**

IoT deployment within a low-tech tilapia culture environment is addressed to gauge effectiveness and expose the impact that can have on small farmers' status quo, as the relevance of abiotic monitoring

for low-tech aquaculture is documented above. While a few operations applying digital technologies to aquaculture of various scales exist, most commercial farms are still run through archaic methods, typically carried out by long-time experience, based on a few water quality parameters manually examined by the farmer or local operators [8].

Since the competences required to monitor and control complex aquaculture environments involve interdisciplinary abilities not available to most farmers, a potential exists for technologies that may increase the operational efficiency, and therefore the yield, of such activities. IoT may thus comprise a major development front potentially capable of cutting-edge dissemination in a coherent cascade involving sensors, actuation, data processing, and monitoring, effectively tying into a wider panorama involving automation, drones, and genetics advancement, among others. While the applied aquaculture IoT is still in its infancy, especially considered from a wider technical perspective, the contribution may nevertheless award valuable insights, as the novelty transcends the mere economic or organizational standpoint.

### **BLOCKCHAIN TECHNOLOGY IN AQUACULTURE**

Today, fish is more important to us than ever before. This is because we depend on fishing – the hunting of fish and their relatives from wild populations – more heavily for food and livelihoods than at any point in the past. With our world population set to increase by 83 million people annually during the next couple of decades, it is all but impossible to conceive how growth can be accommodated without a substantial increase in fish production, sourced from both marine and fresh waters. Because of this, the promotion of the intensification of aquaculture is set to play a key role in ensuring food security and nutrition in several low-income countries of Asia and Sub-Saharan Africa, where the majority of the world's malnourished live. Consequently, in these settings, intensive monoculture of fish species plays a relatively more direct role in recycling nutrients and energy that would have possibly been lost, whilst providing nutrient dense animal protein for human consumption and income for poverty eradication [9].

Passage of fishmeal and oil production from fasciola files using cooler-free plants and time-consuming batches process was abandoned by the beginning of nineties. Now pelagic batch total food fish by-product plant are being used at fishing harbors like Madagascar, Thailand, Fiji, and Mauritius and by-pass mode in Norway. Intensive uses of that plants found environmental and harbor space problems. So, new designs have been carried out which combine fishmeal production with shrimp/prawn processing plant to have value addition. So, the larger factory configuration could include fresh fish handling, freezing area, boat repair center and wastewater control.

### **CYBERSECURITY IN AQUACULTURE SYSTEMS**

With the development of IoT technology, the traditional aquaculture monitoring system has been transformed into an intelligent aquaculture IoT technology system. This monitoring system determines the health of the aquaculture farm sector by monitoring its water quality, feed intake, and more. However, these IoT-based services face obstacles. It is necessary to solve the problems of the intelligent realization of the fish farming system from the cloud ecological agricultural industry, such as system flexibility, scalability and security guarantee, sensor-based data transmission coverage limitation, the want for a certain selection of hardware and software assets, protection of the fish farming method in opposition to safety violations, and intrusion detection and isolation safety liability and phenomena of the important sections of the aquatic approach. Meanwhile, the conventional IoT practice deals with facts and information processing from commercial and retail providers.

In this paper, the definition, architecture, and challenges of traditional aquaculture IoT systems are introduced, leading to the realization of the traditional system weaknesses. After that, the network edge combined by aquaculture IoT technology is proposed. The system with the architecture shown is composed of three-tier structures: aquaculture farms, network edge computing gateways, and cloud software platforms. Additionally, Network-Enabled Capability's working models are designed, including data detection and classification, energy-aware scheduling, monitoring, and visualization

network. Simulation and trial data indicate that the network edge can assist the aquaculture IoT framework in welfare and defense, thus allowing it to regularly supervise and preserve the farming operation of aquatic organisms.

### EMERGING TECHNOLOGIES IN AQUACULTURE

Fishery products play a central role in food security and nutrition. Fish is rich in high-quality protein, essential fatty acids, and various beneficial micronutrients. It is estimated that per capita fish consumption reached a new record of 20.5 kg in 2018, compared to 9.0 kg in 1961. Due to the recognition of its health benefits, the low fat content of the fish and shellfish group and the increase in demand for products such as shrimps, prawns, and crabs. In some Asian countries, it has even replaced meat and poultry as the main source of animal protein. It is estimated that global fish production in 2018 was about 179 million tons, of which 88 million tons were for human consumption and 82 million tons for aquaculture [3].

The global per capita supply of fish for human consumption rose to a new record of over 20 kg in 2018. So far, fish has proven to be the most important source of omega-3 fatty acids, a key nutrient for brain health and development. In view of its potential in the prevention of undesirable freedom such as cardiovascular disease, fish has the potential to become an important alternative source of livestock protein, which is already subject to a certain degree of consumer distrust. Compared to chicken and beef, the protein content of fish is similar or higher, and the quality is better, since it contains all the essential amino acids. Fish breeding also has the advantage that it is vegetative, and there are also cultured species of low-temperature growth waters, which further reduce the ecological pressure associated with the aquaculture production.

### 3D Printing in Aquaculture Equipment

Additive manufacturing (AM) has quickly become a viable option for fabricating purpose-built tools, jigs, and fixtures for aquaculture and research applications. AM is likely to become a standard in business and home aquaculture. Low cost and low expertise necessary for entry make it a favorite for immediate needs. Fused deposition modeling (FDM) is the most common form of AM due in part to the large range of available materials, but ceramic-printed tools show promise for their high chemical resistance. Aquaculture research often involves components that are not readily available. Creating microplates for seed development and live-feed culturing in-house can save time and resources. AM can prototype these in house frequently quicker. AM-printed or modified tools might become commercial items if they meet widespread approval. Equip aquaculture centers with easy-to-produce extruders and Selective Laser Sintering (SLS) or ceramic printers to create a consistent range of recommended and verified tools for stocking home and small businesses. AM-printed mass-producible hatchers are the most viable. AM equipment is likely to become modular in design, allowing precision-engineered prototypes and tools to be replicated by anyone with the correct files. Initially, designs would be shared, or as technology develops, purchased and downloaded instantly. In the home, the aforementioned extruders would recycle print failure and excess filaments into fresh filament to be used in the increasingly integrated AM setups, allowing the user to manufacture a wide range of items.

### Low Cost

The low cost and wide availability of resin printing will be highly disruptive to aquaculture equipment and practical application in the near future. Utilize current kits and open-source knowledge to produce tools and parts on demand. Many printers can be configured to print with negligible modification: better quality and success rates with aftermarket components. Consumer-grade resin printers offer rapid prototyping potential in microfabrication due to their low cost and increasing availability compared to traditional fabrication systems. Research the capabilities: fabricate various microdevices using three different consumer-grade printer models, each with different XY resolution limits, and compare the results to microdevices made using traditional methods as smart plating templates. Improve the fabrication quality of resin printing with features as small as 20  $\mu\text{m}$  to approach traditional methods using a combination of alterations made to pre-processing, post-processing, and printer configuration

steps. These improvements can result in printed objects with sharper edges and smoother surfaces. The dimensional discrepancy of printed features can be less than 5%. The research is of interest to those needing custom microdevices but who do not have access to a microtechnology research center. The limiting factor would be the cost of fabrication considering the average cost and production time based on trial findings. This new technique can prove that opportunities for low-cost microfabricated devices to experiment, optimize, or investigate can quickly expand as printing costs are continually reduced, and as the resolution and quality of finished prints improve. With consumer-grade printers now offering features below 10  $\mu\text{m}$ , fabrication begins to be explored with opportunities and applications in all areas of aquatic bioscience from a culture of microorganisms through studies on embryos to the development of drug delivery systems for mature animals. Limitations in current printing, which are likely to disappear with the growth of resin printing and will be tackled by manufacturers aiming to improve their products. This is the need to replace the screen after about 3000 h of printing. This would appear to be a significant problem as replacement costs in some cases are more than half that of the entire printer. Fortunately, it is expected that advances in technologies will also work towards improving their lifespan.

### **Virtual Reality and Augmented Reality Applications**

This section will link up how virtual, augmented, and mixed realities mesh with marine and industrial aquaculture, leaning into computer modeling and how data is visualized. Some really "far out" technology applications will be shared, along with some stuff you can get started on right away. And finally, this includes stuff about sending Remote-Controlled (RC) boats around using computers and skills to build both the boats and the programs to control them so they do interesting work automatically.

Virtual reality (VR) and augmented reality (AR) – along with their strange offspring, mixed reality (MR) – are mind-bending technologies that have been teased to come to the market since the term “cyberspace” was first coined back in 1982. Until just the past few years most VR/AR/MR real-world applications were seen as pretty hokey. Now, the resolution and refresh rate of digital displays required to convince the human brain that it is in a real world are quickly dropping in price [10].

In aquatic agriculture, what are some of the VR/AR possibilities? Augmented reality on wearing those goofy visor things on heads to uncover hidden treasures or allow robotic physiotherapy following a stroke. Finally! Such incredible tomfoolery joins the mainstream! But, for real, there are researchers and tech companies investing hefty sums into how to mix real AC and DC voltages; those custom, platinum cathode tips – so important to stimulate the optimal, synchronized flutter of neural impulses; and what the color pixels on a high-definition (HD) display show when the imagery is fittingly propagated from software that runs 360° in an endless loop. Judgements are being reserved until success hinges upon someone else’s urgent socioeconomic crisis [11].

### **CHALLENGES AND OPPORTUNITIES IN THE INTEGRATION OF AQUACULTURE AND COMPUTERS**

Owing to better quality cheap protein present in fish and the absence of epidemic problems, fish has great potential to become an important substitute for livestock and poultry protein [3]. Fishery products are playing a central role in food security and nutrition strategies around the world. It is estimated that global fish production in 2018 was about 179 million tons, of which aquaculture accounted for 82 million tons. In the past 40 years, the average annual growth rate of China’s aquaculture output value was 6.6%, which is much higher than the 3.1% of the national economy. China has surpassed Japan and Western Europe to become the world’s leading fish exporter. It is generally recognized that the aquaculture production has played an important role in the food safety of China’s nearly 40 billion population.

However, the agricultural labor force engaged in fishery production is gradually aging and there is a labor shortage in aquaculture. Overfishing, pollution, and other factors have damaged the water quality of fishery production, destroyed the aquatic ecosystem and caused more frequent diseases. Many of the important aquaculture production areas in China and abroad are artificially created, and they are on the

---

bay side and coastal landscape is beautiful. But they are facing the increasingly stringent environmental protection policy of aquaculture, and the situation of aquatic biological diseases is getting worse. According to the survey report of the Federation of Fisheries, as of the end of August 2017, the Ministry of Agriculture has organized and implemented 406 performance investigations and peer inspections, and the pass rate is 71.4%. The lower applicants often do not meet the local actual situation, and the applicant making materials for the policy may also need to be consumed. Moreover, as of the end of September 2017, after the Ministry of Agriculture has issued a list of 87 'unqualified candidates', the local bulletin has identified 2.2 times as much as the total amount in the instructions for 74.9%. In recent years, the process of historical alternatives in the fishery production tradition has placed the fishery industry at a bottleneck. At the same time, the average annual growth rate of global aquaculture production has continued to decline. Aquaculture is facing complex challenges, but there is also a bigger opportunity to develop it in new fields.

### **Data Privacy and Ownership Concerns**

Fish and shellfish farming is big business, farmed fish production is increasing, and it is considered the fastest growing food sector. With increased food security comes an increased risk of environmental damage and disease. Computer technology, including robotics and systems control, is increasingly used in an attempt to mitigate and manage these risks whilst maintaining productivity and profitability [12]. There is, however, little systematic knowledge of the interdisciplinary 'state of the art'. How technical advances drive and are driven by changes in the biological and physical science of aquaculture are therefore reviewed. On the technical front, there is a worrying trend, in the West at least, of large-scale centralization of fish farms by multinational corporations. Information on this sector is, however, almost impossible to obtain. Technological developments in tomographic imaging and non-metallic sensors have the potential for significant advance if not immediately in the public arena. Surveillance camera technology is also advancing rapidly; heavy use, especially in cages at sea is controversial from animal welfare and social standpoints, not to mention data security. System control for fish-rearing is generally more advanced than for shellfish; aquatic weed farms have been largely unsuccessful due perhaps to losses caused by major diseases and predators. Disease control is, not surprisingly, the major problem for both fish and shellfish and the investment in this technology is growing as various 'prophylactic' veterinary drugs become less acceptable to an increasingly informed public. Antibiotics are still widely used. Biosecurity plays an increasingly important role in systems design. Substrate moistness, temperature, pH, oxygen, and dissolved solids sensors are used in a variety of research programs and niche commercial applications. The various ways in which broadband connectivity is used is of interest. Broadband in the ocean deeps despite international agreement is likely to be restricted to regions where it does not interfere with military communications. Who will control the filters from networked fish farm and other environmental sensors? The other side of this coin is the 'freedom of information' aspect in that the use of non-species specific antibiotics is probably common on some Scottish fish farms since it is the only explanation for the treatment of diseases for which there are no licenses.

### **Infrastructure and Connectivity Issues**

The development of fishery modernization depends on the innovations and applications of new technologies. With the rapid development of computers and the increasing diversification of aquaculture cultivation systems, it is possible to achieve high efficiency, large scale, and intelligent management of modern fish farms by interdisciplinary integration of fisheries-related technologies. Edge computing and new intelligent aquaculture IoT systems is proposed to provide a technical work for the development of intelligent modern fish farms [3].

The aquaculture industry has grown rapidly, with revenue amounts in the billions. Meanwhile, the development of computers is rapid. The number of global internet users has increased exponentially. Also, the technology has been widely used for the distributed development and deployment of software systems. Thanks to recent technological innovations, data collection and sharing have become easier. Fish farms can enhance their capabilities with respect to breeding supervision and disaster prevention

by deploying advanced computer technologies. However, many fish farms are located in isolated places—having no power non-local internet infrastructures. This is especially common in underwater cultivation (e.g., the cultivation of salmon, trout, tilapia, prawns, and softshell turtles). As a result, feeding fish at such farms is much less efficient, and there is an increased likelihood of parasite infestation, or disease proliferation. The infrastructure problem is serious and is aggravated by the equipment being submerged in seawater where water erosion is guaranteed to occur. Technology should strive to obviate these drawbacks, work to facilitate the wide deployment of advanced technologies across fisheries, and to trigger its further growth on a global scale.

### **Skills and Training Needs**

The increased need for information and communication technology (ICT) by fish farmers in Rivers State, Nigeria.

Interested in what/how ICT devices and gadgets are used by respondents? Mobile phones, radio, television, the internet, e-mail, blogs, journals, magazines, computers/data storage devices or drives, telephone, SMS, video, multimedia, voice, telemedicine, other? (yes, please specify other – state exactly)

Fish farming/production information needs? Information on pond construction, management, nutritional requirements of fish and feeds, health/sickness/disease issues, disease treatment; stocking, sources of fish/fingerlings, breed; harvesting, preservation, sales/marketing; transportation, storage; government programs/fish farming subsidies/appraisal; prices in different markets; rain water harvesting; market information/prices; feeding, breeding techniques, role in economy; data about production environment; contribution of the aquaculture and fishery sectors to gross domestic product; illegal fishing or collusion with illegal fishermen, middlemen and buyers, quotas? (yes, please specify). (open-ended question for all issues, please provide detail as much as possible).

ICT roles in using/facilitating fish farming/production? Information of fish farming tips and ideas; prices of agriculture inputs; price information on harvest sales; information exchange platform for supply and bars fishing; knowledge sharing among fishermen/fish producers and other supply chain actors; rural marketing and price information; real-time information online access related to weather, fishery; limiting area/season where/when fishing banned; fishermen could not survive due to financial and skill problems affected by fishery resource depletion; multimedia learning materials on fish production; Education promotion program for fishers/fish farmers; online stocking information platform; fishing zones and fishing activities; update information to trace back activities; easy access to publication on fisheries sector allowing them to have a market vision; monitor illegal fishing activities. how are these applications are made? Also could you provide publications on it? (open-ended question for all issues, please provide detail as much as possible).

Problems of using ICTs by fish farmers? High cost of the devices; problems of extremely low education levels and inability to understand standard instruction manuals; non-availability of power and erratic power cut if available; network problems; fish farmers are so far unaware of the potential utility of the computer system and the internet; farmers are so far unable to easily see the knowledge and research available on the internet; information is not in the local language; preference in interaction due to the lack of ict culture; agriculture extension department; ensure that product of mariculture/fish farming is exported; Involvement of provider of marine products to become an agent with importer. (open-ended question for all issues, please provide detail as much as possible).

### **REGULATORY FRAMEWORKS AND POLICIES FOR AQUACULTURE AND COMPUTER INTEGRATION**

The Global Conference on Aquaculture, organized by the United Nations' Food and Agriculture Organization (FAO) and the US Department of Agriculture (USDA) in 1995, was the first aquaculture conference involving the participation of computer professionals from the US Department of

---

Commerce. The conference discussed the application of computers in aquaculture. An international academic exchange seminar on intelligent aquaculture in Yantai, China, in 2000 [3] served as an opportunity for computer specialists to learn about the development of aquatic products in China and to analyze the trend of aquaculture water quality monitoring instruments in China for aquatic products. Computer technology application, computer-aided drafting, simulation and modeling of biological processes, hardware and software developments, information databases, and interfaces between fishing industries were also topics discussed.

Innovations in aquaculture systems in the Asia-Pacific region, including indoor recirculative system and outdoor flow-through aquaculture system, were presented in an exposition of modern aquaculture technology in Asia-Pacific countries in order to disseminate modern technology and computer applications. Vessel traffic management systems (VTMSs) implemented in developed countries for ports, offshore oil platforms, and floating bases shall be considered to help develop the necessary tools to join a VTMS and to integrate aquatic products and aquafeed information into present or planned aquatic trade centers. Computer software is being developed that will allow a user with knowledge of the local weather, water temperature, dissolved oxygen, feed practices, stocking, and water condition to select and rank the best aquatic species, or combination of aquatic products and sizes, to stock at a certain time in a predicted period of time. Such a system is expected to help develop business decisions that will improve the competitiveness of the species in the volatile aquatic trade industry.

#### **CASE STUDIES IN SUCCESSFUL IMPLEMENTATION OF AQUACULTURE AND COMPUTER TECHNOLOGIES**

In view of the practical problems such as the degradation of offshore fish stocks, the increasing demand for fish and marine pollution, fish and the destruction, it is imperative for the aquaculture revolution to change from traditional experience aquaculture to digital intelligent aquaculture. Modern emerging technologies such as AI, big data, sensors, miomers, and critics will gradually participate in the aquaculture production process. Real time water monitor on production environment and big data analysis based on real time intelligent decision making will be the most important thing. A new concept of the intelligent fish farm is proposed, and the application of new generation information technology in aquaculture is briefly reviewed. The introduction of intelligent measurement and control systems, along with automated feeding, inspection, and harvesting equipment, is transforming modern fish farming into fully intelligent operations. The design and implementation of intelligent fish farms, particularly in resource-rich regions, provide valuable reference points for advancing digital, unmanned aquaculture — an endeavor more complex and ambitious than conventional water-based intelligent farming. Mobile micro-robots equipped with sensors are being deployed to monitor and regulate aquatic environments, while various intelligent systems must be integrated to ensure efficient operation. The rapid development of these farms is supported by robust infrastructure and favorable government policies, offering a strategic opportunity for other aquaculture enterprises to upgrade technologies, attract skilled talent, and adopt advanced practices. Ensuring the sustainable and efficient operation of intelligent fish farms relies on clear metrics such as the sustainability index and overcoming challenges related to remote management and environmental uncertainty.

#### **FUTURE TRENDS AND DIRECTIONS IN AQUACULTURE AND COMPUTERS**

Users and computer innovations play an important role in improving global food security, safety, and people's livelihood. Aquaculture and computer science are subjects of broad global interest. The intersection of aquaculture and computers can further promote the sustainable development of the aquaculture industry. In recent years, computer-aided tools, machine learning, and AI technologies have been applied to new problems related to aquaculture. Intelligent fish farms have great potential and broad market prospects for further development. This section provides an overview of the field, providing examples and reviewing relevant selected works [3]. There are subsections in the article that correspond to an introduction and background, the concept of fish production and the potential of intelligent fish farming, management of an intelligent fish farm, automatic intelligent of feeding system,

smart prevention and control of diseases (intelligent disease diagnosis and drug feeding robot), and remote control service robot ship of an intelligent fish farm.

## RESULTS

The integration of computer technologies, particularly AI and the IoT, has significantly advanced aquaculture practices, leading to innovations that enhance efficiency, sustainability, and productivity.

### AI and IoT Innovations in Aquaculture:

- *Smart feeding systems:* AI-driven systems analyze real-time data from sensors and underwater cameras to optimize feeding schedules and quantities, ensuring adequate nourishment while minimizing waste and environmental impact.
- *Water quality management:* IoT-enabled sensors monitor critical parameters such as temperature, salinity, pH, and dissolved oxygen, facilitating real-time adjustments to maintain optimal aquatic conditions.
- *Disease detection:* Advanced image analysis and machine learning models process visual data to identify early signs of diseases, enabling prompt interventions and improving fish health.
- *Behavior monitoring:* AI systems track fish behavior, providing insights into growth patterns, welfare, and responses to environmental changes, which inform management decisions. [thefishsite.com](http://thefishsite.com)
- *Biomass estimation:* Computer vision and machine learning techniques estimate fish biomass accurately, aiding in resource management and operational planning.
- *Automation and robotics:* Robots and automated systems perform tasks such as feeding, cleaning, and monitoring, reducing labor costs and enhancing operational efficiency.

### Recent Research and Developments

- *Digital twin technology:* Researchers have developed multifidelity digital twin models for real-time monitoring of structural dynamics in aquaculture net cages, improving management and operational efficiency.
- *IoT-based water quality prediction:* Studies have introduced IoT-based systems that predict water quality in biofloc aquaculture, enhancing decision-making and productivity.
- *Remote sensing for aquaculture monitoring:* Computer vision methods applied to satellite imagery have enabled the identification and measurement of marine aquaculture production, aiding in data collection and management.

These advancements underscore the transformative role of computer technologies in modern aquaculture, offering solutions that address industry challenges and promote sustainable practices.

## CONCLUSION

In conclusion, the integration of computers, AI, and IoT technologies in aquaculture has brought about significant advancements that enhance both efficiency and sustainability. From optimizing feeding systems and improving water quality management to enabling early disease detection and monitoring fish behavior, these innovations have revolutionized how aquaculture operations are managed. The use of automation, robotics, and advanced image analysis also contributes to reducing labor costs and increasing operational efficiency.

Research is continuously evolving, with the development of digital twins, IoT-based water quality prediction, and remote sensing for aquaculture monitoring offering promising solutions for the industry's future. These technologies not only improve productivity but also help mitigate environmental impacts, offering more sustainable practices for the growing global demand for aquaculture products. Overall, the convergence of computers and aquaculture is paving the way for a more efficient, precise, and environmentally responsible industry.

---

**REFERENCES**

1. Wang C, Li Z, Wang T, Xu X, Zhang X, Li D. Intelligent fish farm—the future of aquaculture. *Aquac Int.* 2021; 29 (6): 2681–2711.
2. Parker NC. Technological innovations in aquaculture. *Fisheries.* 1984; 9 (4): 13–16.
3. Yue K, Shen Y. An overview of disruptive technologies for aquaculture. *Aquac Fisheries.* 2022; 7 (2): 111–120.
4. Dhinakaran D, Gopalakrishnan S, Manigandan MD, Anish TP. IoT-based environmental control system for fish farms with sensor integration and machine learning decision support. *arXiv preprint. arXiv:2311.04258.* November 7, 2023.
5. Parra L, Sendra S, García L, Lloret J. Design and deployment of low-cost sensors for monitoring the water quality and fish behavior in aquaculture tanks during the feeding process. *Sensors.* 2018; 18 (3): 750.
6. Kim T, Lee J, Fredriksson DW, DeCew J, Drach A, Yim SC. Design approach of an aquaculture cage system for deployment in the constructed channel flow environments of a power plant. *PLoS One.* 2018; 13 (6): e0198826.
7. Scuderi B. Assessing Market Integration Among Aquaculture Products and Production Efficiency in New England's Oyster Aquaculture Industry. Master's Thesis. Orono, ME, USA: The University of Maine; 2017.
8. Teixeira RR, Puccinelli JB, Poersch L, Pias MR, Oliveira VM, Janati A, Paris M. Towards precision aquaculture: a high performance, cost-effective IoT approach. *arXiv preprint. arXiv:2105.11493.* May 24, 2021.
9. Enayati M, Arlikatti S, Ramesh MV. A qualitative analysis of rural fishermen: potential for blockchain-enabled framework for livelihood sustainability. *Heliyon.* 2024; 10 (2): e24358.
10. von Lukas UF, Quarles J, Kaklis P, Dolereit T. Underwater mixed environments. In: *Virtual Realities: International Dagstuhl Seminar, Dagstuhl Castle, Germany, June 9–14, 2013, Revised Selected Papers 2015.* Cham, Switzerland: Springer International Publishing; 2015. pp. 56–76.
11. Vasiljević A, Borović B, Vukić Z. Augmented reality in marine applications. *Brodogradnja Int J Naval Architect Ocean Eng Res Dev.* 2011; 62 (2): 136–142.
12. Ascuí F, Haward M, Lovell H. Salmon, sensors, and translation: the agency of Big Data in environmental governance. *Environ Plann D Soc Space.* 2018; 36 (5): 905–925.