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Unlocking the Potential of Internet of Things in Aquaculture: Addressing Challenges and Exploring Future Trends

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Abstract: Aquaculture stands at the nexus of meeting the growing demand for seafood while mitigating environmental impacts and resource constraints. The advent of Internet of Things (IoT) technology offers unprecedented opportunities to revolutionize aquaculture practices, enhancing efficiency, productivity, and sustainability. It can increase the efficiency of aquaculture practice by collecting data from various devices and sensors, which can be used to analyze environmental patterns and fish behavior. However, most aquaculture-producing countries still employ traditional methods instead of modern technology. Numerous cautions and unresolved issues, such as economic and operational viability criteria, accompany the potential of the IoT. A cautious IoT adoption should avoid stranded assets, sunken investment costs, or the long-term ruination of traditional industry knowledge. Most IoT applications in aquaculture remain untapped, and academic research and extension/outreach stakeholders play a crucial role in facilitating knowledge sharing. A proactive approach considering the advantages and pitfalls of IoT in aquaculture can guide businesses and policy decision-makers towards best practices and optimal use of IoT tools and infrastructure. This paper comprehensively reviews the challenges impeding the widespread adoption of IoT in aquaculture and explores potential solutions based on current trends and future projections.

Keywords: Potential of Internet, Addressing Challenges, Exploring Future Trends.

1 Introduction

The Internet of Things (IoT) offers an efficient solution to data analysis in the fishery and remote control/monitor of systems using smartphones or personal computer connected to the internet [1] as shown in Fig. 1. Providing conveniences in the fishery state greatly benefits fish farmers and production. The project has proved successful and has increased the productivity and income of fish farmers by 20%. This example shows IoT is highly applicable to aquaculture and can provide vast benefits [2].

IoT is a system of interrelated computing devices, mechanical and digital machines, objects, animals, or people that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction.

IoT has been employed in various settings and industries and is still developing. IoT can further increase aquaculture practices' efficiency, which could lead to better and higher-quality fish production [3]. The IoT can collect data from various devices and sensors, which can later be used to analyze patterns and human behavior. One project worth mentioning is one run by the National Institute of Fisheries Science in Korea, in which they used IoT to create a smart fish farm management system based on information and communications technology (ICT). The system integrates technology to automatically control the farm facilities, analyze the reproduction and growth of the fish, and keep tracking records [4].

The system uses wireless sensor network (WSN) and RFID technology to connect and manage the devices [3].

Aquaculture is one of the most viable alternatives for sustaining food security and alleviating protein shortages worldwide. Fish contributes about 15% of animal protein and 6.7% of worldwide protein [5]. Asia alone produces around 85% of the world's aquaculture products. However, most aquaculture-producing countries still employ traditional methods instead of modern technology.

Many cautions, considerations, and unresolved issues accompany the potential and promise of IoT [6]. Economic and operational viability criteria are filters through which IoT will succeed or fail in private sector decision

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implementations. 24/7 automated monitoring and interventions must be proven to be more cost-effective than current manual methods or less technologically complex alternative practices [7].

A cautious IoT adoption in the face of industry trends and "irresistible gadgets" should avoid stranded assets, sunken investment costs from failed technology moves, or the long-term ruination of traditional industry knowledge or practice that has arisen from succumbing to technological lock-ins without considering their ramifications. Cause and effect evaluations must ensure that IoT solutions avoid inadvertently creating new problems while solving existing ones [8].

For example, using a chemical alternative to net fouling so that marine mammals accidentally become bycatch on unprotected nets due to reduced acoustic signals can harm marine mammal ecological viability. Moreover, there can be global indirect effects. For example, climate controls for terrestrial livestock systems could cause a relative shift in food animal protein production from land to sea, thereby increasing fish meal demand and placing intensified extractive pressures on global small pelagic fisheries, which are a vital food source and a livelihood for hundreds of millions of the world's poorest people [5].

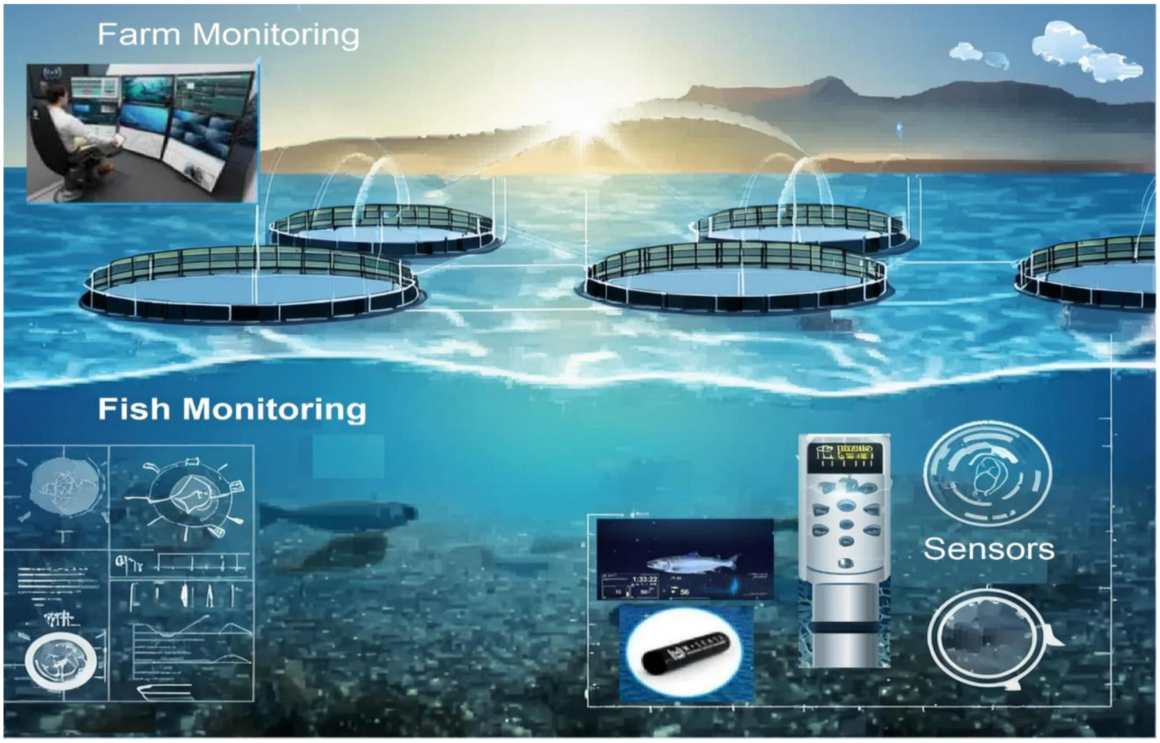

Fig. 1 : IoT in Aquaculture system overview.

In aquaculture, most IoT applications remain largely untapped, in the developmental stage, or are piloted in the private sector with no open access to experiences or data [9]. This is where academic research and extension/outreach stakeholders have a crucial role. In tandem, multi-stakeholder national and global discussions are needed to build consensus on responsible IoT use and governance for sustainable aquaculture production [10].

The IoT begins with sensors to collect data on the farm, in a pond or ocean, or in a hatchery. IoT is a multidisciplinary field and can be used at many points along the aquaculture production chain to provide significant benefits. Here are a few examples: Temperature and dissolved oxygen are critical to fish health. Data loggers and wearable sensors can give real-time readouts, integrated with automatic feeders or aerators, to take corrective actions without human intervention. Acoustic deterrents or safety zones can be established to avoid marine mammal predation or aquaculture animal escape. Monitoring can validate real-time compliance with environmental regulations. Over time, collected data can serve to develop machine learning applications for predictive modeling of the best production practices, comparative risk assessments of management options, or to quantify the cause-and-effect relationships of specific interventions (i.e., disease treatments) on production outcomes. IoT has the potential to significantly enhance fish health and husbandry or compliance and best practice attainment for environmental sustainability [11].

Finally, considering the pace of IoT advancement, it is essential to look around the corner towards future trends so that the aquaculture industry can anticipate and prepare for IoT paradigm shifts that may affect how aquatic food products are produced and marketed.

A proactive approach considering IoT's potential advantages and pitfalls in aquaculture can steer businesses and policy decision-makers toward best practices and optimal IoT tools and infrastructure use. This approach can inform and drive IoT development toward solutions that address environmental challenges and improve the sustainable production of aquatic food products. Advocating for multidisciplinary research that extends beyond engineering and computer science, encompassing social and natural sciences, is essential. The goal is to explore how IoT can effectively comprehend and address the challenges faced within the aquaculture sector.

The aquaculture industry is in the process of undergoing vast changes that are driven by the development of the Internet of Things devices, sensors, and equipment. Through an IoT-based Smart aquaculture system, transformative science can bring forth environmental conservation with more sustainability. In the face of the age of smart aquaculture, the water area research community still has to keep up with the IoT developments to fill the vacant knowledge and perspective upon the smart aquaculture environment [1].

2 Increased Efficiency of Aquaculture Using IoT

Water quality is the most crucial factor in both freshwater and marine aquatic environments. Rapid pH, oxygen, temperature, salinity, ammonia, and pollution changes can lead to detrimental stress or disease in aquatic habitats [12]. If these changes go unnoticed or are not quickly remedied, it can mean the difference between life and death for the animals. IoT technologies are revolutionizing water quality management by enabling miniaturized pH, temperature, and dissolved oxygen sensors to be easily monitored and accessed in real time. A case study in the Czech Republic uses the internet and GIS to gather public data on environmental pollution to assess river water quality [13]. An aquatic autonomous underwater vehicle is designed to evaluate water conditions, detect leaks and illegal waste disposal, and provide valuable data for fish farmers worldwide.

Automated feeding systems enhance fish, animals, and birds' feeding habits in the wild and zoos and work well in outdoor culture [11]. This technology has increased the chances of fishing in fish farms and feeding aquarium fish. Automated feeders enable precise control of feeding times and frequency, reducing labor costs and preventing waste [14]. However, high feed and fuel costs have led to farmers raising fish quickly,

causing water quality issues and disease. Automated feeders help prevent waste and ensure proper feed is used. Trying to maximize fish growth rates has led to overfeeding and, subsequently, lower growth conversion ratios and waste [15]. Step one in water quality management is regulating the amount of feed given to the fish.

Real-time monitoring is the first step to understanding any system. IoT can ensure the same as integrating various technologies, including wireless communication [16], miniaturization, identification technologies, and micro-systems. Wireless sensors can monitor every aquaculture activity and provide real-time data about the aquatic animals and their environment. Miniaturization and labeling data using RFID tags can provide the history of marine animals' activity and environmental changes. Monitoring tray feeding and fish behavior in changing environments is very difficult [17].

Any organization's key to success is high efficiency. IoT can integrate several unrelated processes and provide real-time data, which helps understand the system's pattern. Even though the implementation cost is high, its impact on long-term output will be significant.

2.1 Real-time Monitoring

Real-time monitoring of the aquatic environment can provide farmers with early warnings for environmental problems such as algal bloom, deoxygenation, or pollution events [6]. It can give information about the environment to manage it to achieve an optimum for fish production. Water quality sensors have become smaller, cheaper, and more reliable, resulting in a vast amount of water quality information being collected at high frequencies. High-frequency measurement has benefited from various advances in wireless sensor networking and storage technology. For example, continuous monitoring of water quality changes around trout cages has shown how water quality can change so rapidly that infrequent sampling regimes may fail to detect critical trends [18]. High-frequency tracking has also been done to investigate episodic changes in water quality following an algal bloom.

Observing fish behavior is an essential part of fish welfare assessment. By assessing the fish's behavior, farmers can find out if the fish are in discomfort or are stressed and determine what is causing the fish to behave in that manner [19]. Abnormal behavior might be the only sign of a sick fish when a disease is in its early stages. Real-time monitoring of fish behavior can be carried out using various sensor systems. For example, precision monitoring has been able to monitor salmon behavior during feeding using a passive integrated transponder (PIT) system and a sensor positioned at the entrance to a feeding system. The system successfully monitored fish activity at the feeder over 48 hours. IoT connect sensours with routeers and cloudcomputing to give the user a live stream and fast system feedback as shown in Fig. 2.

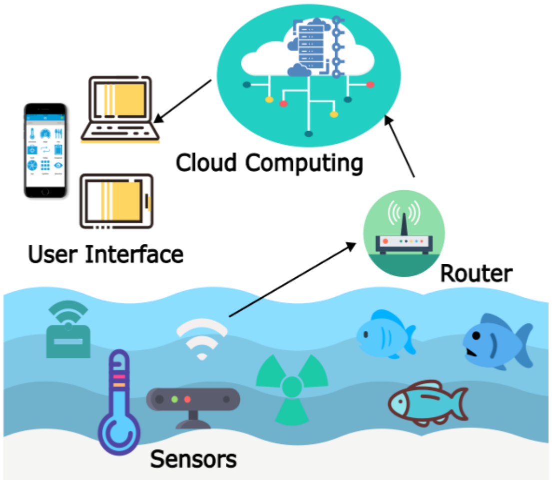

Fig. 2: IoT in Aquaculture system architecture

In the aquaculture production process, as in any farming system, the key areas where real-time monitoring can significantly impact the fish production process are the early detection of problems and providing critical information for decision-making. Real-time tracking can monitor fish behavior and welfare, the aquatic environment, and the fish farm system [20].

2.2 Automated Feeding Systems

Implementing IoT applications such as automated feeding systems can help improve aquaculture efficiency by utilizing real-time data as shown in Fig. 3. Conventional feeding in most farms still relies on human intuition and experience, which can be subjective and costly as different types of feed and frequencies are required for various fish species at different growth stages. Automated systems can monitor fish's appetite at other times of the day, adjusting the amount of feed

dispensed. Some advanced feeders have a weight sensor to prevent over-feeding, and all data on feeding times and consumption are recorded and can be accessed on the cloud. Feeding is one of the costliest inputs in aquaculture, and with an automated system, it is possible to make considerable cost savings.

Fig. 3: Automated Feeding Systems.

2.3 Water Quality Management

Finally, with the advances in Model Predictive Control, it is possible to optimize the use of chemicals such as pH buffers and algicides to control pH and inhibit algal growth. This is highly beneficial in terms of cost reduction for the fish farmer, as the automation will ensure that chemicals are only used when necessary and only at the precise doses needed to maintain water quality within desirable bounds [21].

With the recent advances in recirculating aquaculture systems, IoT technology to control and monitor the ozone level in water has been implemented. An ozone controller can regulate the amount of ozone produced from an ozone generator based on the dissolved oxygen levels in the water, preventing excessive ozone usage. Often, there are separate sensors and control systems as the ozone requirement for treating water and disinfection of water can vary. A band switch control system has been proposed to find the optimal ozone levels for production and fish health, thus switching between high and low ozone. At Saitama University, a band switch control system automatically controlled the dissolved ozone concentration PCR for chum salmon eggs, effectively preventing poor survival rates at high ozone levels. This system is expected to reduce the net loss of ozone from oxidants by over 50%, representing a significant cost saving. Indirect control over ozone can be achieved by controlling the quantities of total oxidants by maintaining ORP values within a specific range. In freshwater fish culture, 300 mV is typically regarded as the safe ORP level [22].

During the past decade, water quality control technology has been introduced to minimize the impact of effluent from aquaculture on the water environment. Reactive oxygen is a commonly used disinfectant in aquaculture. Several fish diseases, parasites, and anaerobic bacteria can be eradicated using ozone without any adverse effects on the fish. Ozone has also been an effective tool in improving seawater quality before its use in land-based aquaculture systems. However, it is essential to note that ozone-dosing water, which is close to fish, can be harmful or fatal.

Photosynthetic activity from phytoplankton and algae can also alter water quality drastically in pond systems, often causing oxygen levels to plummet during the night as they respire. It is possible to use IoT devices and sensor networks that can differentiate between day and night to control the forced aeration systems when oxygen levels in the water are predicted to drop, thus preventing any cases of fish suffocation due to hypoxia.

An example is the recent case of a fish farmer in Idaho, USA, who lost $500,000 worth of fish to suffocation from dissolved oxygen levels reaching nearly zero in a single night [23]. Continued water quality monitoring allows prompt action to rectify a problem before it affects the stock. Water quality monitoring and treatment can be entirely automated by utilizing sensor networks and a Model Predictive Control framework, eliminating human input and simplifying the process for fish farmers, thereby preventing stock damage and increasing efficiency in other management areas.

With aquaculture becoming much more intensive over the past decade, the increase in stock density within the pond enclosures has led to poorer water quality due to the extra solids and waste produced [24]. It is essential to keep a close eye on water quality in the enclosures since the state of the water directly affects the stock and its growth and health status. Using wireless sensor networks to monitor the water quality continually can prevent cases of stock suffocation due to depleted oxygen levels in the water, which is a common occurrence.

3 Environmental Sustainability

Waste in various forms is inescapable in any aquaculture activity, be it excess food waste, nutrients, or feces; an excess of any of these can lead to pollution and damage to local ecosystems. Waste can occur through inefficient use of resources or factors such as overstocking due to miscalculation of fish growth and mortality rates [25]. Automation and control can minimize overfeeding by enabling farmers to calculate precisely how much feed a fish pen requires. Feeding activity can be constantly monitored and adjusted if not consumed due to low dissolved oxygen levels, preventing adverse effects in low-oxygen, tightly packed ponds. Fast detection is vital in cases of oil spills or chemical spills, allowing for immediate action to rectify the situation. Real-time monitoring of environmental factors and abnormal changes alarms as provided by IoT can enable quick detection of any pollution problem.

IoT enhances operational efficiency and aids in resource conservation and efficient use through automation and control systems, which consider resource efficacy and make cost-based decisions [26]. Ecologic, a company specializing in Precision Aquaculture through IoT, states that during farming activities, equipment may cause unintentional damage to ecosystems "by using and extracting too much of a resource, or by depositing waste too quickly for the local ecosystem to process." The company states that farmers can avoid potential ecosystem damage by regulating such activities through intelligent systems that IoT can provide, such as sediment density sensors.

3.1 Resource Conservation

IoT for aquaculture and resource conservation is a relatively new concept with much potential [27]. At present, resource conservation methods are typically ecologically or environmentally based, with few actual technological interventions.

IoT technologies can create a form of "technological conservation" that works with existing methods, often with greater efficacy. Monitoring water quality and aquatic organism well-being by sensor networks can reduce water exchange rates in recirculation systems, conserving water resources [28]. High data rate sensor technology enables precise monitoring of water quality parameters, providing trending data to indicate declining water quality and its suitability for aquatic organisms [29]. This information informs informed decisions on water exchange rates, reducing the conservative approach of exchanging water before it becomes too poor, resulting in significant water savings and maintaining suitable water quality.

Instead of using open-air ponds for fish farming, Recirculating Aquaculture Systems (RAS) enable fish farming in net cages or tanks as shown in Fig. 4 [30].

These devices enable the facility operator to manage the breeding environment and produce fish at great densities. The water is cleaned and recycled by the recirculating system's filters before being returned to the tanks. Only water that has been utilized to remove waste is replaced with fresh water to make up for water lost to evaporation and splashing.

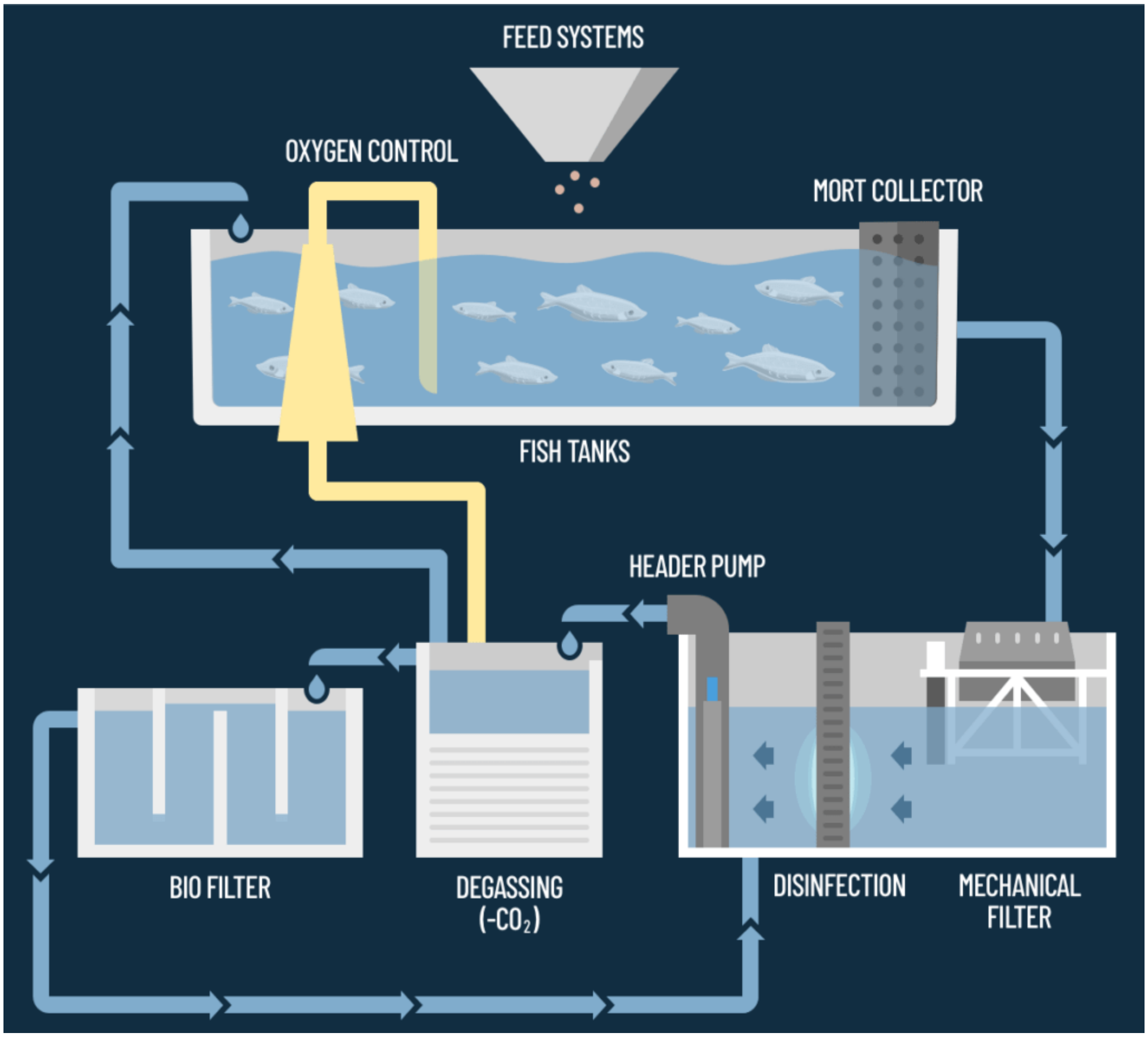

Fig. 4: Recirculating Aquaculture Systems (RAS) [30].

Using water recirculation systems and pond liners for aquaculture practices is the initial and still the most widely used resource conservation method. Water recirculation systems allow for the conservation of water resources. Approximately 70-90% of the total water used for the system is reused, and the remaining <30% is discharged and replenished due to evaporation and water loss to prevent the accumulation of toxins and various metabolites, which would negatively impact the aquatic organisms [31].

The effective use of pond liners maintains water levels in ponds and prevents water loss via seepage, thus conserving water resources. Although pond liners are not suitable for all locations or building designs, developing waterproof ecosystems could create an effective means of water conservation by preventing water loss.

3.2 Waste Reduction and Management

In another case, based on research by Irvine et al. [32] presented an autosampler that can detect nutrient levels in ponds and send information by SMS text messaging. Stopping sampling at high nutrient levels can indicate reduced feeding, reducing the risk of nutrient pollution and algae blooms.

In an expert workshop, M. G. Sharif et al. [33] described a belt feeder system for fish farming. This system dispenses feed when the fish detects an appropriate level of feeding activity. As the system can be calibrated to need no more than 1kg of activity, it is precise and can help prevent overfeeding. This system can be tailored to monitor the fish's activity level through acoustic sensors. The technology can identify their movement and provide a more accurate interpretation of feeding patterns. Like it could be programmed to feed at various points in time, which would eventually avoid repeating, and as a result of this retarding the soil erosion too.

Low-waste and efficient management of waste streams should be crucial elements of a sustainable system [34]. Unmanageable feeding practices give rise to fed surplus and leftovers that fall into the water, causing nutrient pollution. Nutrients like nitrogen and phosphorus in ranges beyond the required amount for the growth of aquatic versions of plants and algal formers occupy the photosynthesis activity that increases the rate beyond normal levels. Dead algae throw away the oxygen that fish need to breathe and, thus, cause local fish to die. Shifting from uncontrolled eating to IoT feeding systems might correct the situation.

Aquaculture production has recently had a unique and impressive revolution, with a considerable growth rate and technological advancements. While the sustainability of industrial practices is still in its infancy, wider commercial adoption is being held back [35].

Increased production of different types of fish, shellfish, and plants has led to environmental problems such as habitat degradation and loss, introduction of invasive species, unregulated use of chemicals and antibiotics, and water and energy consumption. When compared to traditional fisheries, aquaculture has the potential to provide a more sustainable source of animal protein. IoT strategies can help bring this to fruition.

3.3 Ecosystem Monitoring and Preservation

The health of Singapore's coastal and marine environment can be evaluated by carefully regulated experiments examining species' development, survival, and physiological reactions under stress [36]. This is especially important when considering geographic locations and variations in the global environment. Liver histopathology and mixed-function oxygenase enzymes are two examples of biomarkers and bioassays that offer sensitive and informative effect measurements.

The most common method of monitoring coastal and estuarine water quality is expensive and sophisticated telemetry techniques, usually coupled to various sensor devices and equipment [37]. An example can be found in the Sembawang monitoring station, which was established to assess the environmental impact of extensive land reclamation in the Sembawang area [38]. This station has data on such a comprehensive scale that detailed mapping could be conducted. However, it should be noted that a brute-force approach using more equipment only sometimes acquires more meaningful data. Due to the complexity and interconnectedness of the elements of the ecosystem, a more dynamic and holistic understanding of the environment can sometimes be augmented by observed changes in individual keystone species.

The quality of the coastal zone and estuaries can be assessed with the help of the abiotic parameters of the water, namely pH, temperature, salinity, and dissolved oxygen levels, and the presence and concentration of harmful substances in the water, namely nutrients, metals, toxins, and hydrocarbons [39]. Constant data monitoring and regular mapping exercises allow critical detection and documentation of changes in the environment. This is important given the necessity to establish cause and effect linkages between water changes, potential influences from the land or the atmosphere, and the efficacy of any remedial steps.

4 Challenges in Implementing IoT in Aquaculture

Data security and privacy concerns are issues in many industries when implementing IoT, and aquaculture is no exception. With the amount of sensitive information, such as trade secrets and proprietary methods in the aquaculture industry, ensuring the safety of this information is crucial. Additionally, if IoT systems collect data from public waters, it often needs to be clear who owns said data and what it can legally be used for. IoT can also be seen as a potential risk for the spread of disease in aquaculture. Suppose IoT systems are used to automate specific processes. In that case, it can mean that workers will have less contact with conspecifics, and this can increase the chances of releasing animals into the wild, which can potentially interbreed with native conspecifics and cause adverse ecological effects.

Aquaculture is a multifaceted industry that utilizes different techniques in various environments. However, most aquaculture operations generally occur in remote environments such as oceans, rivers, and other large bodies of water. Due to the nature of the aquaculture industry, it is often challenging to have reliable internet connectivity in remote locations. This limited connectivity can be a significant roadblock in implementing IoT in aquaculture, as IoT relies on

a steady internet connection to transmit and receive data. Aquaculture operations can only get valuable real-time data from their IoT systems with a reliable connection.

4.1 Limited Connectivity in Remote Aquaculture Locations

Cellular systems have higher power requirements than Wi-Fi and are associated data with higher usage. This is not ideal for the current low-power, low-data IoT system generation. Machine-to-machine type SIM cards are now available [40], which can be set to only work with specific IoT systems and have a lower cost, though these are still more costly than regular SIM cards. Despite these drawbacks, cellular-based systems are still the best solution to connectivity issues. IoT development should focus on these systems to maximize their effectiveness in transmitting data. When cellular systems still do not provide sufficient connectivity, shelving plans for IoT implementation may be necessary until rural internet infrastructure improves.

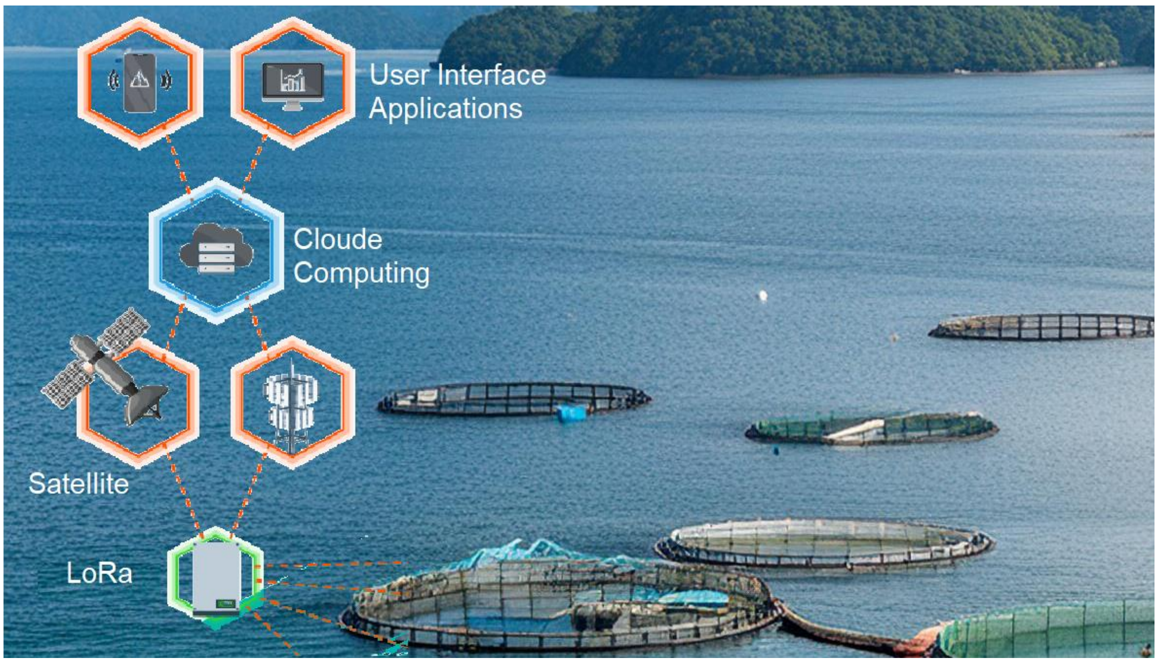

Fig. 5: Connectivity in Remote Aquaculture Locations.

A key challenge in implementing IoT systems in aquaculture farms, particularly in maritime cages, is the limited connectivity of internet systems, especially in more remote areas where many fish farms are located [1], [4]. These areas often have limited or no broadband internet access and using satellite systems can cost more than the potential benefits the IoT system could bring. However, the option to use cellular-based systems is becoming more viable with the growth of 4G and 5G coverage, even in some remote areas. Unfortunately, these systems are still less reliable than traditional broadband connections and can suffer from black spots. A novel approach involves combining LoRa communication systems with satellite or cellular communication, as depicted in Figure 5. This is a significant barrier to the implementation of real-time systems. Matching the cost of these systems to the value of IoT information will be a challenge.

4.2 Data Security and Privacy Concerns

An analysis of data protection in precision agriculture provides insight into how farmers' perception of data sensitivity affects their willingness to adopt precision aquaculture technologies. Farmers' worries that sharing yield monitor data could reveal private company information are acknowledged in the study [1,41]. Should the farmer's production figures fall short of what consumers anticipate, this could be detrimental to them.

Precision agricultural technologies, which collect data that farmers can retain and manage themselves, are therefore more likely to be adopted by farmers since they prevent illegal access to and use of their data. This perfectly reflects worries in aquaculture, where farmers would rather keep sensitive data to themselves.

While the connectivity issues can be addressed by improving technology and decreasing costs, the concern with data security and privacy may still act as a significant barrier to the implementation of IoT in aquaculture. Trust is crucial, and often, the farmers may not want to divulge that they have suffered security breaches due to the damage it may cause to their reputation. The 2013 global survey on IoT's current and future state in the industrial sector conducted by the business information provider Penton showed that more than 70% of the 370 respondents had already experienced an IoT-related security breach. 30% of the respondents from the industrial sector claimed that it would take a data breach for their company to prioritize increasing IoT security. These statistics show how real data security threats are and may make an industry that is declining in profitability less willing to implement new technology to increase efficiency.

4.3 Integration of IoT with Existing Infrastructure

Fish farmers have used various tools to manage their farms and operations. Using IoT to modernize things presents a challenge. This is because the operation-specific knowledge and working practices have been based on conventional methods with low or intermittent adoption of any form of IT [42]. Consequently, many systems are paper or spreadsheet-based, making data gathering for IoT systems difficult. Integration of IoT systems with existing farm management tools needs to be a straightforward task for the fish farmer if the benefits of IoT are to be realized. This will mainly be the case in minor operations and developing countries, where a failure to realize the potential of new technology due to system complexity will result in the rejection of technology. Connecting simple, low-cost devices to a data-gathering system, which requires minimum expert IT knowledge and resources, will be a crucial success factor. Providing the fish farmer with appropriate data analysis and decision-making tools is also vital. Consumer-grade analysis tools are often inappropriate, and decisions based on data are critical to the farmer's business. The farmer must be convinced that the new IoT systems directly replace his existing methods with clear added benefits. This implies that for some systems, there will be a gradual migration to IoT over the years.

5 Potential Solutions and Innovations

In terms of an industry-wide strategy, QR has suggested that harnessing technology and global market transparency can provide improvement in the long run. This strategy depends on whether Malaysia can continue developing its aquaculture market to the level of resource abundance that created the tragedy of the commons in the first place.

This method requires newer workers to take the initiative and ITQOL in aquaculture, using educational tools to inform the necessity of effectively managing resources and the environment. With the country rich in aquatic resources and an industry still growing, the potential to increase productivity and raise the standard of living is realistic.

Over twenty years have passed, and the situation in Malaysia has only improved further within the industry. This empirical research demonstrates how the aquaculture industry needs to adapt to technology and find more effective ways to optimize its work. Evaluating the results of this method provides a realistic outlook on the issue. It shows that Malaysia can become a significant player in the global market by halting this trend and reversing it to high productivity.

A recent economic analysis of aquaculture in Malaysia, using 1998-2007 secondary data, revealed both positive and negative news. While the industry grew, the number of resources it used could have resulted in maximum economic productivity. Although resources have increased, the industry is using less labor, and with declining returns to scale and an overall decrease in productivity, traditional tools and methods have become less effective.

5.1 Development of IoT Sensors

Automatic samplers can also collect water samples, which can be analyzed later, allowing specific lab analyses to be performed.

However, this data collection method is slowly becoming obsolete with recent online developments in sensor technology.

Online water quality sensors can measure specific parameters and provide continuous data at high frequencies. This can say something about the diurnal or episodic variability of a given water quality parameter. An example is measuring the concentration of a particular pollutant during a storm event, which may only be captured using continuous monitoring. This would be missed using traditional grab sampling and subsequent lab analysis. Step motors can control the depth at which the sensors are monitoring.

Traditionally, monitoring watercourses has been constrained by the cost of retrieving data manually from isolated gauging stations and the ad hoc nature of water sampling. This has meant that the data collected needs to be more timely, sufficient, and representative. Water quality measures are often made in the lab on water samples, analyzing various pollutants, nutrients, and chemical properties. Although this provides highly accurate data, it can be costly and time-consuming, and continuous long-term data on water quality needs to be provided.

The sensor is essential in any IoT system as it allows the physical environment to be monitored and measured, creating actuators to provide a measurable response. Sensor technology has advanced rapidly, and many different types of sensors are available, cheap enough to deploy in large numbers. This section will outline the various kinds of sensors available for environmental monitoring and how they can be utilized in aquaculture.

5.2 Integration with Artificial Intelligence

Prediction and control systems are more advanced than expert systems. They can determine a system's future condition and influence it to reach a desirable condition with minimal error. This prediction and control system is suitable for disease prediction and prevention in aquaculture. An example of this is the disease path prediction in sea cage farming of groupers using artificial neural networks. By learning from available data on sea conditions and disease attacks, this system can predict disease paths and suggest the best prevention methods [43].

Simple decision-making based on rules and logic can be automated using an expert AI system. Research on hybrid intelligent systems for spatial decision-making can be seen as an early step in the sophisticated implementation of AI in aquaculture. A decision support system constructed by blending case-based reasoning (CBR) with other AI techniques can be considered a highly flexible tool for emulating human decision-making.

The IoT framework and its key components all gather data required for decision-making. This data cannot be described accurately using a rule-based expert system, which requires an expert in a specific topic. Statistics and machine learning have been proven to be flexible methods for modeling a system or solving complex problems. These two methods can be considered data-driven models constructed from available data and basic knowledge of the system. There is a wide array of AI implementations in the aquaculture industry, ranging from simple automation or prediction to advanced robotic systems. AI aims to reduce human work on trivial and repetitive tasks, creating a system that can learn independently and make decisions that match or surpass human professionalism.

5.3 Cloud Computing for Data Analysis

Cloud computing stores and accesses data and programs over the internet instead of your computer's hard drive [26]. It involves using a network of remote servers hosted on the internet to store, manage, and process data rather than a local server or personal computer. Cloud computing is already used in several industries, particularly the technology sector. The advantages cloud-based processing possesses over the traditional data processing method by a server, or a local computer are huge. First, cloud processing is cheaper than traditional data management approaches. When using cloud computing, the cost is based on what is consumed, so there are no prevailing initial expenses. Cloud services can make data analysis much cheaper than servers, which requires a lot of cleaning and energy consumption.

The cloud tightens business resources from the possibilities of downplaying in migration and upkeep of the servers, which the cloud service provider’s handle. The scalability of cloud computing is another good fight, for it can cope with scaling. This supports aquaculture operations, as the periodic nature of data analysis might not reach continuously through the process, and the data collection amount can vary. Last, the cloud computing capability of data retrieval and analysis enables a device to function in any location, even in remote areas, and has made it a good solution for aquacultural sites located in distant places. As opposed to the local server data analysis, which implies the data movement to the server by using

physical devices such as USB, this concept may restrict the site of the analysis to the vicinity of the server. Cloud computing appears to be the most beneficial data analysis alternative since IoT and aquaculture are already migrating into it, and in the near future, they will choose it.

6 Future Trends in IoT for Aquaculture

Future trends in IoT for aquaculture indicate the trajectory toward which the industry is moving. The more data can be collected and analyzed from sensors and cameras; the more automation can be implemented in various farm systems. Currently, many IoT devices are focused on specific tasks such as monitoring water oxygen levels or counting fish when they pass a certain point. Future systems could autonomously control equipment and make decisions based on data analysis, such as automatic oxygen or feed level adjustments in fish tanks or water flow systems that adjust speed and direction for optimal fish health. Farm managers will monitor and adjust all these systems from remote locations, saving time and money. An example of this kind of future system is being developed for the wastewater treatment industry, which has many parallels with aquaculture. Recently, an automated system combined real-time data from aeration equipment with an artificial intelligence engine to control dissolved oxygen levels in water and reduce energy usage. This system could be implemented for fish health in a pond or tank with the same AI technology and oxygen sensors.

6.1 Automation and Remote Monitoring

IoT development in aquaculture is still in the early stages, yet it is progressing toward automation and monitoring, which will strongly affect how fish are raised [44]. There are some prominent trends to watch in the development of IoT for aquaculture.

Automation and remote monitoring in aquaculture have significantly improved feeding, with machines dispensed at set times or self-learning feeding systems, making it a task already largely automated in modern aquaculture. These systems use data from water sensors and fish activity and adjust the feeding strategy according to the conditions. An example of an early-stage feed machine is the 'pendulum' type feeder, which consists of a motor that turns a set of gears and rotates a disc that scatters the feed out of holes and into the water. An example of a more advanced feeding machine would be the 'fluidizing' type feeders, which utilize a fan that blows air up through a hopper containing the feed, which suspends the feed and causes it to flow out of a pipe at the bottom of the hopper. Although these machines are classified as 'automated,' they do not adjust to the conditions and will feed the same amount regardless of what is required.

Remote monitoring allows for remote systems monitoring, particularly in large settings like aquafarms. By placing sensors in each pond, a computer can monitor data and receive warning signals if specific conditions are met, eliminating the need for regular visits to check water conditions.

6.2 Predictive Analytics and AI in Aquaculture

AI has also assisted this kind of prediction. AI has been used to simulate fish growth environments and produce the best outcome for growth rates and fish health. It is being done through various intelligent software systems. An example of future AI prediction software in aquaculture has been using fuzzy logic to manipulate inputs to optimize fish production. Such software has been used in the Philippines milkfish industry with the GrouFish model [45]. AI simulations are utilized to optimize feed inputs for maximizing the best economic outcomes as evidenced by studies employing linear programming and models like EFA/PL in fish farms in SW Scotland, which have reduced feed usage while maintaining product quality [46].

Aquaculture is now getting into predictive analytics by using numeric data sources and past/future predictors to precisely model the stocking, growing, and harvesting of fish and shrimp species. Mathematical models, such as dynamic state variable models used in the Tasmanian Atlantic salmon industry, suggest effective management strategies that maximize net present value [47].

Predictive analytics employs statistical techniques, including modeling, machine learning, and data mining, to analyze historical and current data, enabling automated decision-making, actions, and strategic planning within organizations.

6.3 Integration with Blockchain Technology

The potential impacts of using blockchain technology are genuinely profound. Underpinning all other developments in the IoT for aquaculture, it offers the possibility to revolutionize the industry from wild catch to farmed product, vastly increasing efficiency and improving the sustainability of the global seafood industry [45].

A blockchain-based framework enables access to global information resources and rapidly provides accurate and comprehensive information services to various seafood industry and supply chain entities. Using ID tags and readers, data is collected throughout the aquaculture supply chain, from the point of production to the final product. This data is, in turn, linked to the physical product, enabling complete traceability throughout the product's lifecycle.

In their work, the authors [45] propose a speculative system that ensures transparency and data integrity by employing fishing observers as data collectors to record all fishery activities and data onto a public blockchain. This approach supports adopting blockchain technology, aiding Regional Fishery Management Organizations in implementing cutting-edge electronic reporting systems.

Wild Capture Information System aims to transform seafood sustainability by building a public system for collecting and sharing information to improve the management of the world's captured fisheries. To ensure the reliability, traceability, and immutability of data input, blockchain is proposed as the foundation for establishing Smart Certified Seafood. Blockchain promises to reassure consumers that the seafood they purchase is certified and harvested in compliance with all relevant laws and regulations.

Blockchain has been touted as a game-changing technology across various sectors, promising transparency and security by design. In aquaculture, there is growing interest in adopting blockchain to enable traceability of products back to their originating farms. This transparency provides consumers with information about the product's origins and allows farmers to calculate a higher price for their product.

7 Conclusions

Though IoT offers numerous advantages, the aquaculture industry is a small-scale industry that could be more organized and decentralized. Making technology available and affordable, even to small-scale and marginal farmers, will be challenging. Developing various IoT systems and platforms will require a significant investment by multiple stakeholders. Therefore, identifying issues related to technology adoption in aquaculture and developing strategies to address these issues is essential if the full potential of large-scale technology platforms is to be realized. Government and non-government organizations need to frame suitable policies to provide incentives to adopt these technologies. While developing IoT systems and platforms, involving the end users and gathering their feedback and suggestions is essential to make the systems more useful and user-friendly.

IoT is an emerging technology that can shape aquaculture's future. Through this paper, we have addressed the challenges faced by the aquaculture industry and have proposed using IoT to overcome these challenges. Various real-time and non-real-time applications have been discussed, which have the potential to increase the yield of the farm and potentially save the farm from losses due to diseases, environmental conditions, etc. The farm's profitability can be improved by smart management of resources and the farm. With the help of intelligent automation, fish can be monitored and treated with optimal medication. They can be grown under the best environmental conditions for their reproductive, growth, and maturity stages. Releasing these various stages of fish at the right time can prevent market fluctuations and ensure a steady market price throughout the year. We also discussed how IoT can help ensure the best quality and compliance of the final product.

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