ADVANCING SUSTAINABLE AQUACULTURE THROUGH WATER QUALITY MONITORING AND TECHNOLOGICAL INNOVATIONS

Abstract

The monitoring of key physico-chemical parameters for aquaculture water quality is of paramount importance in fish farming. This chapter delves into the critical parameters that influence fish survival and development, including pH, electrical conductivity (EC), oxidation-reduction potential (ORP), and turbidity. Maintaining optimal conditions within defined ranges is essential for fish health and productivity, as deviations can lead to stress or even mortality. Furthermore, specific water quality criteria for pond water fishery are outlined to achieve high yields with minimal inputs. The integration of advanced technologies such as wireless sensor networks (WSNs) and embedded systems has revolutionized water quality monitoring in aquaculture. WSNs offer remote data capture and real-time monitoring, enhancing efficiency and providing insights into environmental conditions. Embedded systems, equipped with ZigBee, GSM, Cloud, MSP430, and Lab View technologies, enable precise control and monitoring of critical parameters. In addition to WSNs and embedded systems, various automatic monitoring systems, including IoT-based solutions, RF, GSM, GPS tracking, artificial neural networks (ANN), computer vision, and specialized sensor platforms, have emerged as valuable tools for aquaculture farmers. These systems enable real-time data collection, predictive capabilities, and insights into fish behaviour, ultimately promoting sustainability and efficient farming practices. The integration of technology with aquaculture holds the potential for a

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future where data-driven insights and sophisticated monitoring systems take a pivotal role in nurturing aquatic life and safeguarding the sustainability of the aquaculture industry.

Keywords: Water quality monitoring, Aquaculture, Technological Innovations, Sustainability

I. INTRODUCTION

Aquaculture has emerged as a rapidly growing field due to the global surge in demand for seafood. Among various seafood options, fish stands out as a highly sought-after choice, largely owing to its recognized health advantages. The practice of fish farming holds substantial sway over the economies of nations, given the escalating desire for fish. Indian aquaculture constitutes a pivotal segment within the food production landscape, catering to nutritional security, providing livelihood support, and creating employment for over 14 million individuals. The estimated fish production for 2017-18 stood at 12.60 million metric tonnes, with nearly 65% derived from the inland sector. Culture fisheries accounted for around 50% of the total production, contributing approximately 6.3% to the global fish production. Often, water quality receives inadequate attention in the management of ponds or lakes, leading to a cascade of issues. Neglected water quality can result in problems such as excessive algal blooms, uncontrolled plant growth, unpleasant odours, or even fish mortality. The paramount importance of water quality in aquaculture cannot be understated. It serves as the chief determinant influencing fish health and performance within aquaculture systems. However, a considerable number of countries find themselves compelled to import fish due to insufficient domestic production. To illustrate, in Ghana, the supply of fish from both aquaculture and capture sources falls short of meeting half of the country's demand. As a response to the shortfall in supply, aquaculture has gained paramount significance in the advancement of the fisheries sector across many nations. This shift is particularly crucial as the limitations on supply are projected to persist and potentially intensify in the future. The reason for the growing significance of aquaculture in the fisheries sector is that it offers a sustainable and controlled method of seafood production, which can help meet the increasing global demand for fish and seafood while alleviating pressure on wild fish stocks that are often overexploited. Aquaculture encompasses a range of practices, knowledge, and methods used for cultivating aquatic plants and specific animal species. This endeavour holds significant importance in both economic advancement and the production of food resources. Consistently observing the physical, chemical, and biological attributes of pond water serves a dual purpose: not only does it enable the anticipation and management of adverse conditions in aquaculture, but it also prevents harm to the environment and potential disruptions to the production process. Regularly tracking key factors like oxygen levels, temperature, water clarity, and pH within the water body is essential for sustaining favourable conditions and preventing undesirable scenarios that could jeopardize the stability of aquaculture systems. Effective fisheries management hinges on the observation of water quality, given the prevalence of fish diseases that significantly influence the quantity of the harvest obtained [1].A common error committed by aqua culturists involves excessive feeding, leading to the accumulation of unconsumed food that can result in water pollution. To prevent unfavourable circumstances for cultivation, it is crucial to consistently monitor key factors within the tank, including pH levels, dissolved oxygen, water levels, ammonia concentration, and temperature [2]. The feeding pace, rate of growth, and general well-being of the fish are contingent on the quality of the water. The necessity to closely observe aquaculture indicators becomes essential in light of potential diseases and diminished output that could stem from suboptimal water conditions.

II. SCOPE OF THE AQUACULTURE WATER QUALITY MONITORING

This chapter primarily centers on the potential of a water quality monitoring system within fish farming. The monitoring of water quality holds a pivotal role in influencing the survival and developmental progression of fish. Even a minor alteration in water conditions could exert stress on the fish, possibly resulting in fatality. In contemporary intensive fish farming, more sophisticated technological systems have emerged to ensure the maintenance of optimal water conditions. Broadly, a water quality monitoring system for aquaculture typically encompasses components like given below [3].

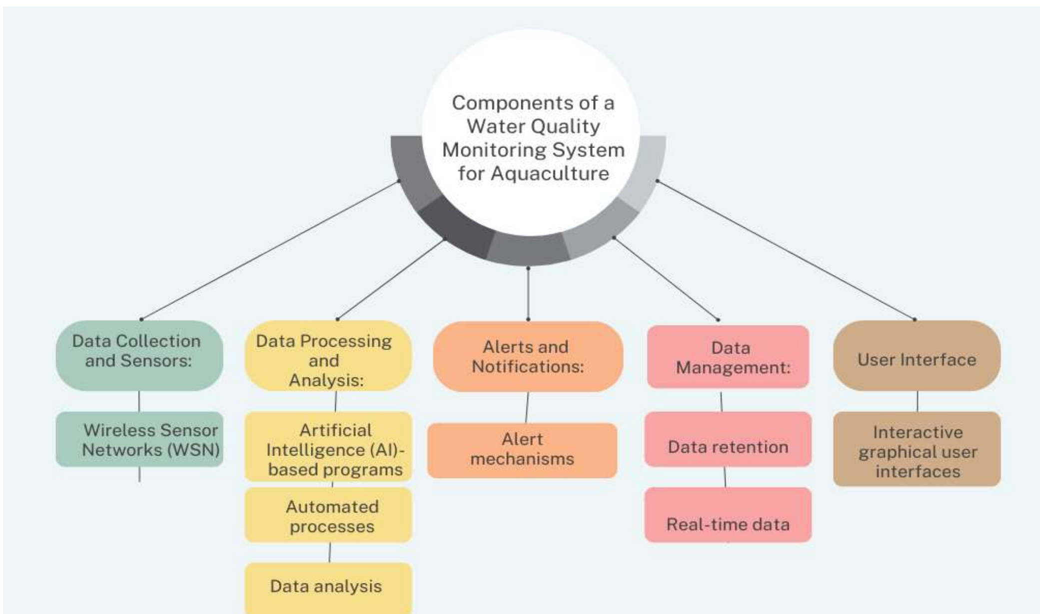

Figure 1: Key Components of a Water Quality Monitoring System for Aquaculture

III. KEY PHYSICO-CHEMICAL PARAMETERS FOR AQUACULTURE WATER QUALITY

1. **pH:** pH serves as a gauge of the acidity or alkalinity of a solution. A pH value of 7 denotes neutrality, while values below or above 7 indicate acidity or alkalinity, respectively. In the context of aquaculture ponds, maintaining a pH within the range of 7.5 to 8.5 is typically advised. Fish production can be significantly influenced by pH levels that are either too low or too high. In fact, extreme pH values have the potential to be fatal for fish. Additionally, these extreme pH conditions can hinder the growth of natural food sources for the fish. The critical pH thresholds vary depending on factors such as the specific fish species, the size of the fish, and the overall environmental conditions. It's worth noting that fish tend to be more vulnerable to extreme pH levels during their reproductive seasons, with eggs and young fish being more sensitive than their adult counterparts [22].

2. **Electrical Conductivity:** Electrical conductivity gauges a solution's capacity to conduct electrical current. It is indicative of the presence of conductive ions, usually originating from dissolved salts and inorganic substances. A higher salt concentration corresponds to higher conductivity. Distilled water registers a low conductivity of 0.5 to 3µS/cm, while streams range from 50 to 1500µS/cm. In freshwater streams suitable for aquaculture, the recommended conductivity should fall within 150 to 500µS/cm. Different fish species have varying tolerance levels for EC. Too high or too low EC levels can stress or harm fish. High EC can indicate the presence of excessive dissolved solids, which can affect osmoregulation in fish. Low EC can indicate insufficient mineral content, which can also impact fish health. When water salinity levels are either excessively high or low, it can lead to fish mortality because they struggle to maintain their internal balance (homeostasis)[23].

3. **Oxidation-Reduction Potential (ORP):** ORP quantifies the propensity of electrons to move between components within a solution, reflecting the water's ability to eliminate contaminants. Elevated ORP readings are indicative of healthy water conditions ORP influences the availability of dissolved oxygen in water. Low ORP levels can indicate poor oxygen availability, which is critical for fish respiration. Inadequate oxygen can lead to fish suffocation and stress, potentially causing fish mortality.

4. **Turbidity:** Turbidity assesses the quantity of suspended and colloidal materials within water and is measured in nephelometric turbidity units (NTU) or Jackson's Turbidity units. Drinking water should exhibit turbidity levels below 1 NTU. Aquatic organisms thrive within a turbidity range of 5 NTU to 50 NTU. Excessive mineral and humic turbidity in water limits the penetration of light, leading to reduced photosynthesis and lower oxygen production during the daytime. This lack of light negatively impacts both fish growth and the abundance of their natural food sources. Furthermore, elevated mineral turbidity can directly harm fish by damaging their respiratory organs, slowing their growth, and even inhibiting their ability to reproduce. Similarly, it can have detrimental effects on small aquatic organisms like cladoceres and copepods (zooplankton), which serve as vital food sources for young fish [22].

Table 1: Suggested Water Quality Criteria for Pond Water Fishery for Getting High Yield Via Applying Minimum Inputs

S. No.	Parameter	Acceptable Range	Desirable Range	Stress
1.	Temperature (^{o}C)	15-35	20-30	<12, >35
2.	Turbidity (cm)		30-80	<12,>80
3.	Water colour	Pale to light green	Light green to light brown	Clear water, Dark green &Brown
4.	Dissolved oxygen (mg L^{-1})	3-5	5	<5, >8

5.	BOD (mg L^{-1})	3-6	1-2	>10
6.	CO_2 (mg L^{-1})	0-10	<5, 5-8	>12
7.	pH	7-9.5	6.5-9	<4, >11
8.	Alkalinity (mg L^{-1})	50-200	25-100	<20, >300
9.	Hardness (mg L^{-1})	>20	75-150	<20,>300
10.	Calcium (mg L^{-1})	4-160	25-100	<10, >250
11.	Ammonia (mg L^{-1})	0-0.05	0- <0.025	>0.3
12.	Nitrite (mg L^{-1})	0.02-2	<0.02	>0.2
13.	Nitrate (mg L^{-1})	0-100	0.1-4.5	>100, <0.01
14.	Phosphorus (mg L^{-1})	0.03-2	0.01-3	>3
15.	H_2S (mg L^{-1})	0-0.02	0.002	Any detectable level
16.	Primary productivity (C L^{-1} D^{-1})	1-15	1.6-9.14	<1.6, >20.3

Table 2: The Water Quality Preferences for Some Commonly Cultured Species in India

Species	**Temperature ºF**	**Dissolve oxygen mg/L**	**pH**	**Alkalinity mg/L**	**Ammonia %**	**Nitrite Mg/L**
Baitfish	60-75	4-10	6-8	50-250	0-0.03	0-0.6
Catfish/Carp	65-80	3-10	6-8	50-250	0-0.03	0-0.6
Hybrid striped Bass	70-85	4-10	6-8	50-250	0-0.03	0-0.6
Perch/Walleye	50-65	5-10	6-8	50-250	0-0.03	0-0.6
Salmon/Trout	45-68	5-12	6-8	50-250	0-0.03	0-0.6
Tilapia	75-94	3-10	6-8	50-250	0-0.03	0-0.6
Tropical Ornamentals	68-84	4-10	6-8	50-250	0-0.03	0-0.5

IV. APPLICATIONS OF WIRELESS SENSOR NETWORKS

Water Quality monitoring systems have undergone substantial improvements through the integration of wireless sensor networks (WSNs), a technology that has garnered recent attention due to advanced communication techniques. These networks represent a significant and promising emerging technology, holding substantial promise for enhancing various applications within the realm of intensive aquaculture [4]. WSNs excel in remote data capture and transmission, operating independently of fixed network infrastructures. Their notable communication efficiency stems from minimal power consumption, making sensor nodes highly energy-efficient and particularly attractive in the context of aquaculture [4]. One of the remarkable features of WSNs is their intimate connection to the immediate physical surroundings. This capability enables individual sensors to provide comprehensive insights into environmental conditions that would otherwise be challenging to acquire using conventional wired instruments [5]. Within the domain of Water Quality Monitoring (WQM), WSNs have seamlessly integrated themselves by offering versatile solutions for diverse control and monitoring applications. These networks represent straightforward and cost-effective systems for remote, real-time monitoring, often requiring minimal human intervention. A typical WSN configuration consists of sensor nodes and a central base station. Sensor nodes play a pivotal role in monitoring various parameters and possess the capacity to both sense and transmit data. In contrast, the base station serves as a hub for connectivity, facilitating data transfer and remote node management. Data relay within these networks frequently utilizes low-power communication standards such as IEEE 802.15.4, ZigBee, and Bluetooth. In practice, Wireless Sensor Networks (WSNs) effectively capture data pertaining to critical variables like pH levels, water temperature, water level, and dissolved oxygen. This data is transmitted to a centralized database and subsequently fed into software systems for real-time monitoring [6]. ZigBee technology is often employed for transmitting data collected by sensors in WSN-driven water monitoring systems [7].

In summary, the integration of wireless sensor networks into Water Quality Monitoring systems offers a potent blend of remote monitoring, energy efficiency, and versatile data capture capabilities, making them invaluable tools in the field of intensive aquaculture.

This general flow illustrates how wireless sensor networks contribute to monitoring and maintaining water quality in fish farming environments, ensuring that the conditions are conducive to fish survival and productivity

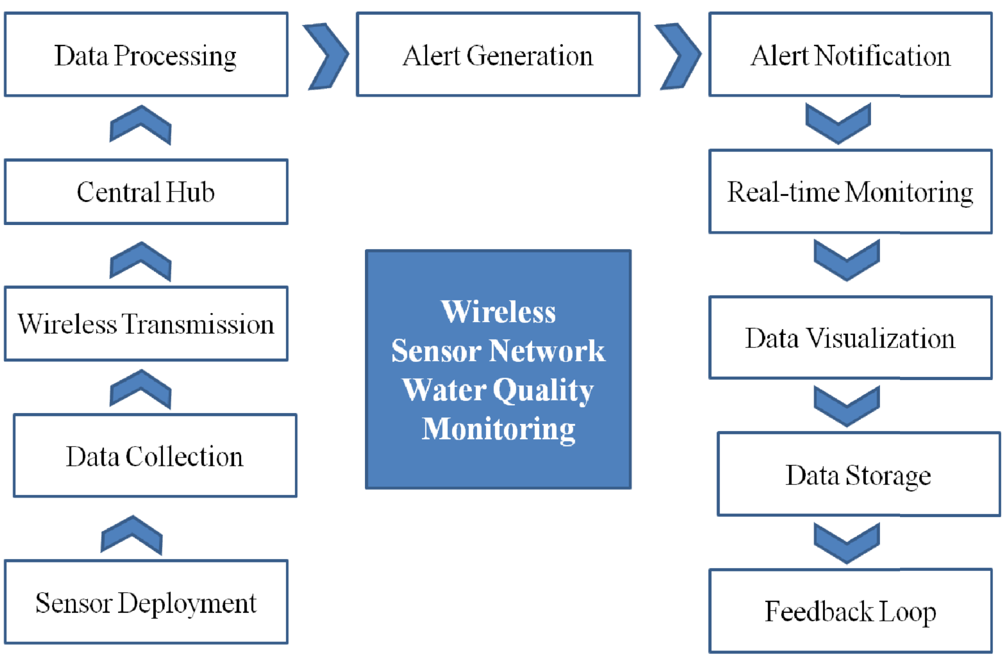

Figure 2: Wireless Sensor Network Water Quality Monitoring in Fish Farming: Process Flow

V. EMBEDDED SYSTEMS IN AQUACULTURE

An embedded system is a specialized control and operating system meticulously crafted for a particular purpose, typically within a broader mechanical or electrical framework. These systems often operate under stringent real-time computational constraints and are seamlessly integrated into comprehensive devices, integrating both hardware and mechanical components. The world of embedded systems governs a multitude of devices we encounter in our modern lives. In fact, an overwhelming majority, approximately 98%, of microprocessors find their home as integral components of these embedded marvels. In the realm of aquaculture, the potential of embedded systems shines brightly, especially in the context of shrimp farming water quality monitoring and automated control systems. These embedded systems can be harnessed effectively, ushering in a new era of precision and efficiency. By integrating technologies like ZigBee, GSM, Cloud, MSP430, and Lab View, embedded systems take on a dynamic role in managing critical environmental conditions and controlling essential processes [11]. Envision a ZigBee-based wireless sensor network (WSN), where a series of low-power embedded MSP430 microcontrollers collaborate to monitor and control environmental parameters such as pH, water level, water temperature, and dissolved oxygen. As depicted in [11], these embedded systems vividly illustrate the dynamic variations in these vital metrics. Over the course of six months and throughout the day, they meticulously record communication performance, battery efficiency, and sensor readings, providing a comprehensive view of the aquatic environment. Moreover, the integration of IoT-based systems in aquaculture introduces tangible economic advantages, as elucidated in [12]. Through a series of experiments conducted within farm environments, the adoption of IoT systems scrutinized, contrasting the expenses and resource utilization with farms not benefiting from such advanced systems. The results spoke volumes, revealing a reduction in costs ranging from 19.34% to 6.03%, with an average of 3.98%, in farms that embraced these IoT-driven solutions. In this intricate symphony of technology and aquaculture, embedded systems play a pivotal role, orchestrating precision, efficiency, and cost-effectiveness [12]. These systems, with their real-time capabilities and tailored applications, hold the potential to revolutionize the way we monitor and manage the aquatic environments essential to the thriving world of aquaculture.

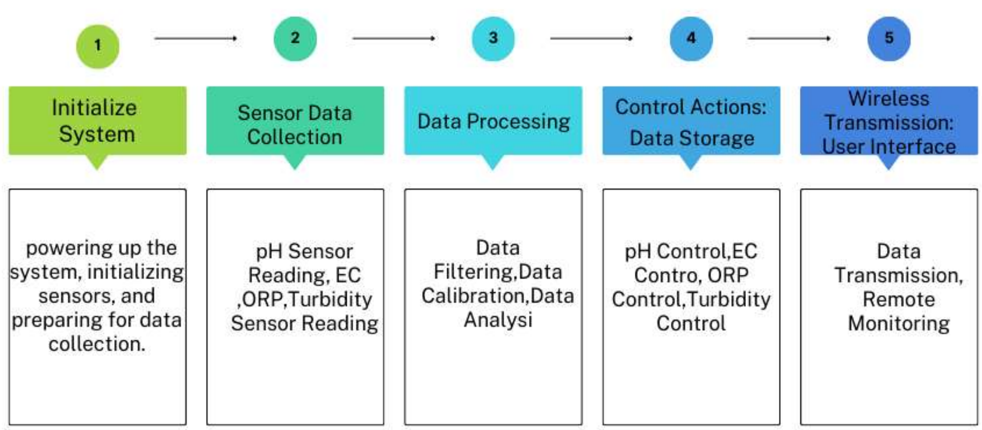

Figure 3: Embedded System Water Quality Monitoring in Fish Farming

VI. OTHER AUTOMATIC MONITORING SYSTEMS

Automatic monitoring systems have emerged as valuable tools empowering aquaculture farmers to efficiently oversee their operations, ultimately enhancing the well-being of aquatic organisms and promoting sustainability. IoT technology finds utility in water quality monitoring of aquaculture systems by facilitating the transmission of data over the internet [19].For instance, [13] introduced a innovative aquaculture environment monitoring system that harnessed the capabilities of RF (Radio Frequency) and GSM (Global System for Mobile Communications) technologies. This innovative system not only measured temperature and dissolved oxygen levels but also incorporated two intricate algorithms. One algorithm evaluated the performance of the central monitoring center, while the other scrutinized various substations. These substations tirelessly collected data around the clock, relaying real-time information to the central system. The result was a harmonious orchestration of data flow and analysis. Moreover, GPS tracking devices, as illustrated in [14], have emerged as instrumental tools in monitoring the free-ranging behaviour, distributions, and population structuring of aquatic organisms. These devices exhibit impressive accuracy, with an approximate positional precision of 70 meters. Sunfish of varying sizes, ranging from 0.6 to 1 meter, were tracked to create insightful trajectories visualized on maps. Furthermore, the system captured speed data, elegantly presented in graph form alongside the aquatic route, offering valuable insights into aquatic behaviour. Artificial neural networks (ANN) stepped into the spotlight in [21], demonstrating their prowess in predicting water quality trends and mitigating potential losses. In [15], a sophisticated data collection node was introduced, equipped with an array of sensors measuring vital parameters. This included water and room temperature, dissolved oxygen saturation percentage, dissolved oxygen concentration, pH, electrical conductivity, and salinity. The integration of ANN technology provided aquaculture farmers with predictive capabilities that are indispensable for maintaining optimal conditions. Meanwhile, computer vision technology, as explored in [16], entered the stage by concurrently monitoring fish behaviour in nine tanks. This innovative approach assessed stock density as a stress factor, providing real-time visual insights. The findings, especially from experiments conducted with undamaged mesh, brought to light significant statistical differences in aquatic behaviour. For mobile aquaculture environments, [17] contributed a tailored mobile sensor platform comprising sensing nodes within each pond, all connected to a central sink. This setup facilitated real-time data visualization through a mobile application and leveraged GSM/3G connectivity for internet transmission. The result was remote monitoring capabilities and efficient data storage in a centralized database. Furthermore, [18] introduced a specialized water quality monitoring system designed for fish farms. Leveraging the SUNSET (Software Defined Communication Stack) for networking and Hydrolab Series 5 probes for data acquisition, this system meticulously measured various critical parameters. These included temperature, pH, luminescent dissolved oxygen (LDO), salinity, oxidation-reduction potential (ORP), and specific conductance (SpCond). Lastly, a comprehensive survey of vision-based systems conducted in [20] delineated the primary applications of optical sensors across different aquaculture phases. Technologies such as machine vision, hyperspectral imaging, thermal imaging, and x-rays were explored in the context of fish monitoring. These applications were thoughtfully categorized into five distinct types: fish sorting, fish quality assessment, physical attributes measurement, chemical attributes assessment, and food security enhancement, underscoring the versatility of optical sensors in advancing aquaculture practices. In this symphony of technological advancements, aquaculture is poised for future where data-driven insights, real-time monitoring, and predictive capabilities take center stage, nurturing both aquatic life and sustainable farming practices.

VII. CONCLUSION

The concluding observations extracted from the literature assessment are as follows: The scope of aquaculture water quality monitoring is vast and critical for the success of fish farming. Each fish species exhibits specific water quality requirements (temperature, pH, oxygen levels, salinity, hardness, etc.) within which they can thrive, develop, and reproduce. The preservation of consistent and favourable water quality conditions is imperative, as polluted water poses a threat to habitat suitability. This chapter has emphasized the significance of monitoring water quality in fish farming operations, as even slight changes in water conditions can have detrimental effects, potentially leading to fish mortality. Addressing these aspects involves diverse methodologies, with the integration of Internet and Wi-Fi technologies offering enhanced convenience and cost-effectiveness. The integration of advanced technologies, such as wireless sensor networks (WSNs) and embedded systems, has revolutionized the way we monitor and manage aquatic environments in aquaculture. WSNs, with their remote data capture and real-time monitoring capabilities, offer efficient solutions for monitoring parameters like pH, temperature, water level, and dissolved oxygen. Embedded systems, when integrated with technologies like ZigBee, GSM, Cloud, MSP430, and Lab View, enable precision control and monitoring of environmental conditions, contributing to the well-being and productivity of fish. Furthermore, various automatic monitoring systems, including IoT-based solutions, RF, GSM, GPS tracking, artificial neural networks (ANN), computer vision, and specialized sensor platforms, have emerged as valuable tools for aquaculture farmers. These systems provide real-time data collection, predictive capabilities, and insights into fish behavior, ultimately promoting sustainability and efficient farming practices. As we move forward, the fusion of technology and aquaculture holds the promise of a future where data-driven insights and advanced monitoring systems play a central role in nurturing aquatic life and ensuring the sustainability of the aquaculture industry.

VIII. FUTURE PROSPECTS

The evolution of IoT technology holds immense potential for the detection of chemical parameters in water, allowing for real-time monitoring and control. Leveraging IoT and Wireless Sensor Networks (WSN) opens doors to innovative projects, including the establishment of Smart City initiatives encompassing energy-efficient street lighting and air quality monitoring. Furthermore, opportunities abound for purifying and filtering contaminated water sources, assessing soil quality, and deploying base stations to oversee water quality across multiple regions. Additionally, IoT capabilities could extend to fish farming by facilitating fish count estimation and health monitoring. By incorporating additional sensors, a comprehensive understanding of both physical and chemical water quality determinants can be attained. This knowledge is pivotal in ensuring water quality is maintained at optimal levels. A significant avenue for exploration lies in assessing the energy consumption of IoT devices. This insight is crucial for optimizing energy-efficient operations within IoT-based systems. Furthermore, by introducing automation into aquaculture practices, labor costs and energy consumption can be markedly reduced. This progress would signify a shift towards a more sustainable and resource-efficient aquaculture industry. The convergence of IoT and WSN technologies promises transformative developments in water quality management, environmental monitoring, and aquaculture practices. The potential to enhance efficiency, accuracy, and sustainability underscores the exciting prospects that lie ahead.

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