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Internet of Things-Driven Precision in Fish Farming: A Deep Dive into Automated Temperature, Oxygen, and pH Regulation

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Abstract: The research introduces a revolutionary Internet of Things (IoT)-based system for fish farming, designed to significantly enhance efficiency and cost-effectiveness. By integrating the NodeMcu12E ESP8266 microcontroller, this system automates the management of critical water quality parameters such as pH, temperature, and oxygen levels, essential for fostering optimal fish growth conditions and minimizing mortality rates. The core of this innovation lies in its intelligent monitoring and control mechanism, which not only supports accelerated fish development but also ensures the robustness of the farming process through automated adjustments whenever the monitored parameters deviate from desired thresholds. This smart fish farming solution features an Arduino IoT cloud-based framework, offering a user-friendly web interface that enables fish farmers to remotely monitor and manage their operations from any global location. This aspect of the system emphasizes the importance of efficient information management and the transformation of sensor data into actionable insights, thereby reducing the need for constant human oversight and significantly increasing operational reliability. The autonomous functionality of the system is a key highlight, designed to persist in adjusting the environmental conditions within the fish farm until the optimal parameters are restored. This capability greatly diminishes the risks associated with manual monitoring and adjustments, allowing even those with limited expertise in aquaculture to achieve high levels of production efficiency and sustainability. By leveraging data-driven technologies and IoT innovations, this study not only addresses the immediate needs of the fish farming industry but also contributes to solving the broader global challenge of protein production. It presents a scalable and accessible approach to modern aquaculture, empowering stakeholders to maximize output and minimize risks associated with fish farming, thereby paving the way for a more sustainable and efficient future in the global food supply.

Keywords: smart fish farm; pH sensor; IoT; temperature sensor; cloud monitoring; automatic controlling

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1. Introduction

The current world population of 7.3 billion is projected to reach 11.2 billion by 2100, leading to an estimated 70% increase in the demand for protein to nourish this growing population [1]. The conventional reliance on meat as the primary source of dietary protein is becoming unsustainable due to the limitations of traditional agricultural practices. As the global demand for protein increases, so too does the strain on ecosystems, necessitating innovation in food production to meet nutritional needs without further degrading the environment. Oceans, which have long been a crucial source of protein, are already overexploited—currently, 2.5% more fish are harvested annually than the ocean can naturally support. Since 1950, 90% of the most commonly caught fish have vanished from the oceans, according to a World Wildlife Fund (WWF) report [2]. Traditional fish farming methods, although a critical part of global protein production, face several limitations that hinder their ability to meet this growing demand sustainably. These methods are labor-intensive and often inefficient, requiring frequent manual monitoring and intervention to maintain optimal conditions for fish growth, such as water quality, oxygen levels, and temperature. Inconsistent environmental conditions, a lack of real-time data, and the need for on-site personnel to manage farms increase costs and reduce productivity. Furthermore, the environmental impact of conventional fish farming practices, including water pollution and the overuse of resources, exacerbates the challenges of scaling up production to meet global needs. This highlights the urgency of seeking alternative, sustainable methods for protein production, such as fish farming, to complement and reduce the pressure on wild fisheries. IoT-based automation offers a solution to many of the challenges traditional fish farming faces. By providing real-time data, remote accessibility, and precise control, IoT systems enable more efficient, reliable, and sustainable fish farming practices [3–8].

This research explores the potential of the IoT in fish farming, addressing critical challenges such as reducing labor dependence, improving environmental control, and increasing productivity. By integrating various sensors and secure protocols like the Message Queuing Telemetry Transport Protocol (MQTT), fish farmers can monitor and control essential parameters such as pH, oxygen, and temperature in real time. If these parameters exceed predefined threshold levels, the system can notify users through a cloud monitoring platform and automatically adjust environmental controls until conditions return to optimal levels. Compared to traditional fish farming methods, IoT-based systems present significant financial advantages by reducing the need for on-site personnel and optimizing operational efficiency. Previous studies have shown that IoT-based fish farms can yield higher financial returns than non-IoT-based counterparts. With a modest investment of $60 to $70, farmers can implement IoT systems to contribute to solving the global protein challenge.

This paper is structured in five sections, including the Introduction. Section 2 reviews related work, while Section 3 outlines the methodology, including circuit design and smart fish monitoring and control processes. Section 4 presents experimental results, and Section 5 discusses the conclusion and future directions for this research.

2. Related Work

A few studies in modern fish farming encompass a range of techniques and systems tailored to the specific needs of different fish species. These techniques can be broadly categorized into extensive, semi-intensive, and intensive systems. Extensive systems often involve the cultivation of fish in natural bodies of water, while semi-intensive and intensive systems utilize controlled environments such as ponds, raceways, or recirculating aquaculture systems (RAS). Each system has its advantages and challenges, with factors like water quality management, feeding practices, and disease control playing crucial roles [9]. An open-source and cost-effective buoy prototype has been designed for remote water quality monitoring in fish farming. Utilizing LoRaWAN technology for data transmission, this prototype aims to replace conventional manual sampling methods, enhancing efficiency and data availability [10]. The challenges and opportunities presented by IoT-based fish farming have been subject to extensive research, laying the foundation for the current exploration. Earlier studies have underscored the increasing global demand for protein and the strain on conventional agriculture, propelling the need for innovative solutions [2].

Researchers have contributed significantly by highlighting the pivotal role of IoT technologies in fish farming. Their work emphasizes real-time monitoring, automation, and efficient resource management as critical components for optimizing productivity and ensuring sustainability [11–15]. Addressing global food security challenges emphasizes the significance of aquaculture in meeting protein demands [11]. Researchers have further explored the potential of IoT systems in enabling efficient and sustainable fish farming practices, aligning with broader goals of food security [12–14].

On the significance of employing IoT-based monitoring systems in aquaculture, these systems utilize a combination of sensors, microcontrollers, and cloud technology to continuously monitor crucial parameters like pH level, water temperature, and oxygen levels in fishpond environments, as in [16–23]. An overview of IoT applications in aquaculture is given here, focusing on monitoring and addressing water quality issues. Various strategies and smart devices for recognizing live fish, measuring parameters, and tracking aqua animals are discussed, reflecting the growing interest in IoT solutions for aquaculture management. IoT-based automation holds immense potential for revolutionizing the aquaculture industry. By providing real-time data, remote accessibility, and precise control, these systems address the limitations of traditional methods, ultimately promoting more efficient, reliable, and sustainable aquaculture practices.

As per the mentioned research analysis, we have found a lot of innovation in this regard but there is no innovation like automated controlling which features no human intervention; the expense is another challenge and one of the main tasks in building up an ideal fish farming strategy. Our focus is on minimizing the cost of implementing this innovation as well. Additionally, the innovation of IoT-based automatic controlling of temperature, oxygen, and pH will help the fish farmer to produce fish food in a profitable and cost-effective manner over time.

In the context of our different analyses, most farmers follow the traditional system for fish farming, and it is costly and human-oriented rather than the automated IoT-based fish farming method, which minimizes human interactions and is cost-effective as well. As per our understanding, we have found that this is the main obstacle to having a profit-oriented fish farm; this means that better growth of fish is missed by not understanding the related controlling parameters required for the better growth of fish. Additionally, automated IoT-based fish farming through controlling the related fish growth-related environmental parameters like pH, oxygen, and temperature will ensure profit-oriented fish farming and mitigate the protein challenges of the world.

3. Methodology

3.1. Measurement of All Parameters

Measurement is the process of determining the value or quantity of a particular attribute in scientific research and various fields, and accurate and precise measurements are crucial for obtaining reliable data and drawing meaningful conclusions. The importance of measurements such as pH, oxygen levels, and temperature are a very important part of our system's deployment.

3.1.1. pH Measurement

pH is a measure of the acidity or alkalinity of a solution. It revolves around the measurement of hydrogen ion concentration in a solution. It affects chemical reactions, enzyme activities, and the overall health of ecosystems. pH is commonly measured using a pH meter or pH indicator paper. The pH scale ranges from 0 to 14, with 7 being neutral, values below 7 indicating acidity, and values above 7 indicating alkalinity.

3.1.2. Oxygen Measurement

Oxygen measurement refers to the determination of the concentration of dissolved oxygen in a liquid, typically water. Oxygen is essential for the survival of aquatic organisms and is indicative of the health of aquatic ecosystems. Common methods include titration, electrochemical sensors, and optical sensors. Dissolved oxygen is measured in milligrams per liter (mg/L) or parts per million (ppm).

3.1.3. Temperature Measurement

Temperature is a measure of the degree of hotness or coldness of a substance. Temperature can be measured using thermocouples, thermistors, infrared thermometers, or mercury- or alcohol-filled glass thermometers. The unit of temperature is typically degrees Celsius (°C) or Fahrenheit (°F).

Figure 1 demonstrates an overview of the proposed IoT-based fish farming monitoring and automated controlling of the total system, and how the sensor data will be collected and transmitted to the IoT cloud of the system, where the system determines various important features like pH, temperature, and oxygen measurement without any human interaction and has a great impact on the fast development of fish. In the very beginning, to run the system, a certain amount of power is necessary to boost up the system where different types of sensors like pH, oxygen, and temperature sensors have been used. As the pH sensor does not provide a suitable value, we have calibrated the pH sensor with different types of testing, like with normal water, litmus testing, and chemical testing, which also ensured our data accuracy. At specific temperatures, the pH probe provides a specific value, which we calculated by merging results for different pH-related tests conducted in different liquids.

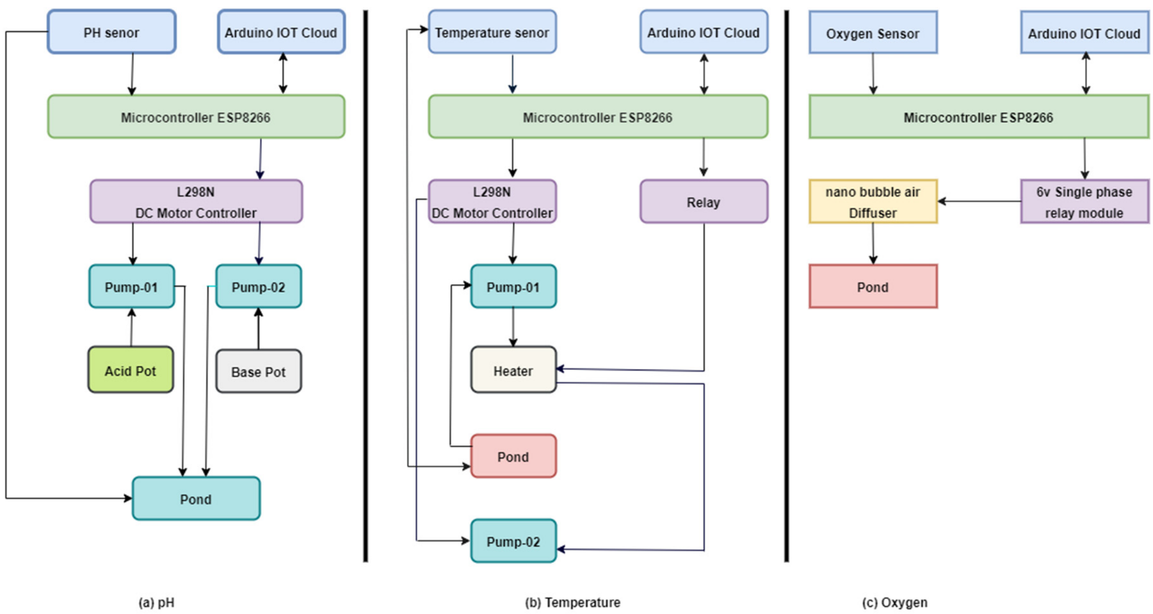

Figure 1. A block diagram of the proposed system.

In Figure 1, the block diagram of the proposed system serves as a visual representation of the structured approach. We have taken to the design and implementation our IoT-based fish farming system. The segmentation of the system into three distinct blocks—pH, temperature control, and oxygen management regulation—illustrates our comprehensive and methodical approach to creating a well-balanced aquatic environment.

Accurate and comprehensive environmental monitoring is crucial for understanding and managing ecosystems, water quality, and industrial processes. In this study, we present an integrated measurement system designed for the real-time monitoring of key environmental parameters: pH, dissolved oxygen, and temperature. The significance of such a system lies in its ability to provide a holistic view of environmental conditions, facilitating informed decision-making and contributing to the broader fields of environmental science and applied research.

The interconnected nature of environmental parameters necessitates a holistic approach to measurement. Traditional monitoring methods often focus on individual parameters, potentially missing crucial interactions. Our integrated measurement system addresses this limitation by concurrently measuring pH, dissolved oxygen, and temperature. This approach enables a more nuanced understanding of environmental dynamics and correlations between parameters, enhancing the accuracy and reliability of the data collected.

To enhance the precision of the system, we conducted various mathematical measurements. The following represents the segmentation of different types of measurements incorporated into our system, accompanied by corresponding mathematical equations.

3.2. Average Temperature Measurement

During winter, the frigid conditions pose challenges for fish as they struggle to feed and undergo growth processes. Our solution uses two temperature sensors that take readings every 10 s. This helps us to obtain accurate data, which is sent to the IoT cloud. We have used two temperature sensors because our system heats water in a jug and then pours it into the bucket where the temperature sensor collects continuous data and passes to the microcontroller. To avoid any mismatch between two sensors, data are collected from different parts of the bucket and passed to the microcontroller. The microcontroller is like the brain. It averages the temperatures from both sensors and sends this combined data to the IoT cloud.

The average temperature T_{average} is calculated over the 10 s interval by averaging the reading from the two temperature sensors.

Temperatures from the two sensors are T_1 and T_2:

$$T_{\text{average}} = \frac{T_1 + T_2}{2} \tag{1}$$

As per Equation (1), a reading is taken from both sensors, which are added together, and then the result is divided by 2 to obtain the average temperature.

3.3. Voltage Calculation of pH Sensor

$$\text{volt} = \frac{avgval \times 5.0}{1024 \times 6} \tag{2}$$

The variable avgval represents the average value obtained from sensor readings. According to Equation (2), it converts the average sensor readings to voltage. The multiplication by 5.0 scales the result to represent a 5-volt range, and the denominator (1024 × 6) adjusts for the 10-bit ADC range and the circuit's sensitivity.

3.4. pH Calculation

$$pH/_{act} = -5.70 \times \text{volt} + \text{calibration\_value} \tag{3}$$

The variable $pH/_{act}$ represents the actual pH value calculated from the sensor data and Equation (3) relates the calculated pH to the voltage measured. The term $-5.70 \times$ volt represents the linear relationship between the pH and voltage, and the calibration value adjusts for any sensor calibration offset.

3.5. Temperature Increase (Heating)

Turning on the heater relay: digitalWrite(heater relay, LOW).

Turning off the heater relay after a certain interval: digitalWrite(heater relay, HIGH).

Turning on the pump for the heating jug: analog Write(pump_heater,155).

Turning off the pump for the heating jug after a certain interval: analog Write(pump_heater,0).

3.6. Temperature Decrease (Cooling)

Turning on the pump for the pond: analog Write(pump_pond,155).

Turning off the pump for the pond after a certain interval: analog Write(pump_pond,0)].

In the provided Arduino code, the value "155" is used in the analog Write function for controlling the speed of the pump. In Arduino, analog Write is used to generate a PWM

(Pulse Width Modulation) signal to control the intensity of an output, such as the speed of a motor or the brightness of an LED. The analog Write function in Arduino accepts values between 0 and 255, where 0 corresponds to the minimum (off) and 255 corresponds to the maximum (full on). So, when "155" is passed to analog Write(pump heater, 155), it means setting the pump speed to approximately 60.8% of the maximum speed. The actual mapping from the 0–255 range to the physical output (e.g., motor speed) depends on the specific hardware being used and its characteristics. In general, higher values will result in higher speeds or stronger outputs, and lower values will reduce the speed or output.

3.7. The PWM Duty Cycle, Represented as a Percentage, Can Be Calculated Using the Formula

$$\text{Duty Cycle }(\%) = \left(\frac{PWM\ Value}{255}\right) \times 100 \tag{4}$$

In the provided Arduino code, "155" is used as the PWM value. The following formula is used:

$$\text{Duty Cycle }(\%) = \left(\frac{\text{PWM Value}}{255}\right) \times 100 \approx 60.8\% \tag{5}$$

So, in this case, the PWM duty cycle is approximately 60.8%. The duty cycle represents the percentage of time the PWM signal is ON within one period. In the context of controlling a motor or pump speed, a higher duty cycle generally corresponds to a higher speed or stronger output.

3.8. Heater Control Equation

The heater is turned on for a specific duration (interval) when the temperature is below a certain threshold (25°). The heater is then turned off after the specified interval. This is a simple time-based ON-OFF control.

$$\text{Heater Status} = \begin{cases} 1 & \text{if temp} < 25 \text{ and flag} = 1 \\ 0 & \textit{Otherwise} \end{cases} \tag{6}$$

where the following hold:

temp is the current temperature.

flag is a control variable indicating the current state.

3.9. Pump Control Equations

Similar to the heater, the pumps are controlled based on time intervals and the value of the flag variable. A mathematical representation of the pump control equation is as follows:

$$\text{Pump\_Pond Status} = \begin{cases} 1 & \text{if temp} < 25 \text{ and flag} = 2 \\ 0 & \textit{Otherwise} \end{cases} \tag{7}$$

$$\text{Pump\_Heater Status} = \begin{cases} 1 & \text{if temp} < 25 \text{ and flag} = 0 \\ 0 & \textit{Otherwise} \end{cases} \tag{8}$$

where the following hold:

temp is the current temperature.

flag is a control variable indicating the current state.

As per the mathematical equation, the ESP8266 microcontroller facilitates the transmission of gathered data to the Arduino IoT cloud within the system. This feature empowers fish farmers with the ability to effortlessly monitor real-time data and assess the current system status from any location worldwide. The web interface-based IoT cloud also offers a graphical representation, enhancing the monitoring experience. Additionally, data are stored in a database repository, providing fish farmers with the flexibility to review past records in various formats such as Excel and PDF.

Moreover, the system is equipped with automatic functionality. If key parameters such as pH, oxygen, or temperature surpass predefined threshold values, the system is triggered into operation. It remains active until adjustments are made to the threshold levels. This proactive approach ensures a seamless and responsive system that maintains optimal conditions for fish farming.

The suggested system is categorized into the following components:

A. Circuit Design and Software

In Figure 2, the proposed system is developed based on the designed circuit depicted in Figure 2. The VCC and ground pins of the pH sensor are connected to the 5 V and ground pins of the Arduino Nano. The pH sensor is linked to an analog pin, and the pH value is derived from the analog output using the pH calculation formula. Two temperature sensors are connected with a 4.7 K resistor, along with the ESP8266-3V, ground, D1, and D4 pins. Components such as the L298N, relay, submersible small pump, and heating jug are connected to the NodeMCU12E microcontroller board following the circuit diagram. The code, written in Arduino IDE and language, is uploaded to the system, ensuring ease of understanding and reliability.

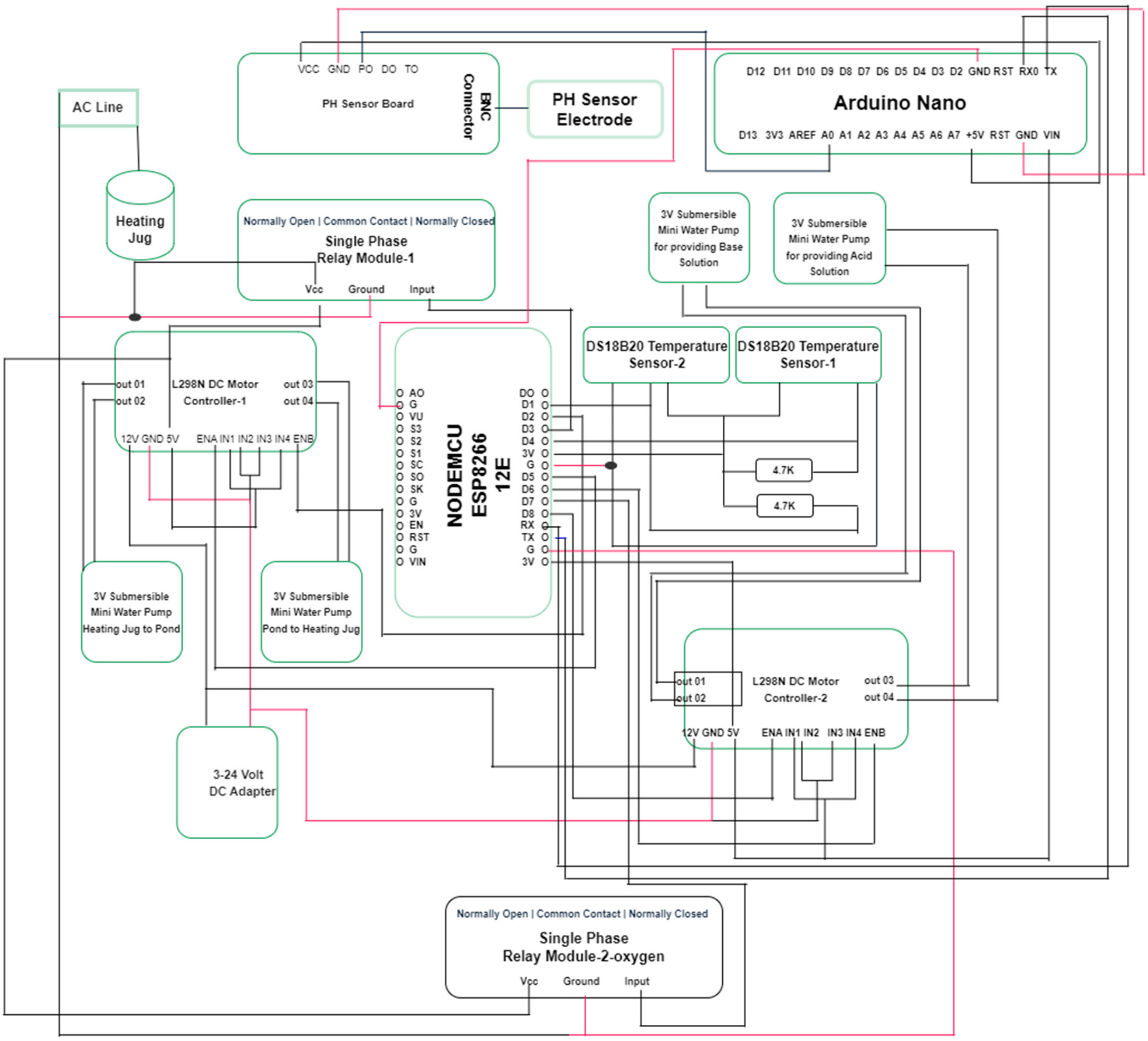

Figure 2. An illustration of the circuit design of the envisioned system.

B. Hardware: the following pieces of equipment are utilized to develop the hardware part:

(1) NodeMcu Esp-12E: the NodeMCU ESP-12E, based on the ESP8266 microcontroller (Microchip Technology, Chandler, AZ, USA), is a versatile and widely used open-source platform, offering integrated Wi-Fi capability and a Lua script interpreter, making it an ideal choice for IoT projects requiring wireless connectivity.

(2) Arduino Nano: The Arduino Nano is a compact ATmega328P-based board with 22 digital I/O pins, 8 analog inputs, and USB connectivity—ideal for space-efficient embedded projects. Compact yet robust, it features an ATmega328P processor, 32KB flash memory, and 22 digital pins.

(3) pH Sensor: a pH sensor measures the alkalinity or acidity of a solution whose scale range is from 0 to 14, where 7 is considered neutral, below 7 acidic, and above 7 alkalic. Gravity is an analog pH sensor equipped to measure the pH level of the fisheries' water.

(4) DS18B20 digital temperature sensor: The DS18B20 is a digital temperature sensor that uses the 1-wire protocol to communicate with a microcontroller. It has a temperature range of −55 °C to +125 °C and a resolution of 9 to 12 bits. It is accurate to a degree of ±0.5 °C over most of its range. The DS18B20 is a popular choice for applications where accuracy and reliability are important.

(5) DC submersible water pump: The DC submersible water pump stands as a cost-effective and versatile component within our IoT-based fish farming system. It exhibits an impressive operational range, spanning from 2.5 V to 6 V, rendering it adaptable to various power sources.

(6) Relays: 1-channel 6 V relay module: A compact relay for controlling one channel of devices using a 6 V signal, offering versatility in automation and electronics projects. "Ideal for automation, this module allows control of a single channel using a 6 V signal, providing a reliable solution for switching applications in various projects."

(7) Nano Bubble air diffuser: Efficiently aerates water with nanoscale bubbles, enhancing oxygen transfer in aquaculture and water treatment systems. "Designed for optimal oxygenation, this diffuser produces fine nanobubbles, improving water quality and supporting aquatic environments in applications such as aquaculture and water treatment."

(8) L298N DC motor driver: Each H-bridge within the chip can conduct up to 2A of current per channel, making it well-suited for driving DC motors. These motors can be employed to control various components within our fish farming system, such as water pumps and oxygen diffusers for efficient control.

(9) Power Adapter: 3v to 24v DC adapter: In the context of our thesis, this power supply module plays a pivotal role in ensuring the continuous and reliable operation of various components within our IoT-based fish farming system.

C. Algorithm

In Figure 3, the system initiates by initializing all sensor values. The pH is calculated every 10 s using the pH formula. Upon detecting the introduction of vinegar-mixed water, the system enters a 1 min waiting period, and similarly, for calcium carbonate mixed water. During these intervals, the system ensures proper dissolution of pH in the water, enhancing data accuracy and reliability. With the optimal pH range for the rapid growth of fish set between 7 and 8.5, the system is programmed to automatically activate and persist until it reaches the preset threshold if the pH surpasses this range [24].

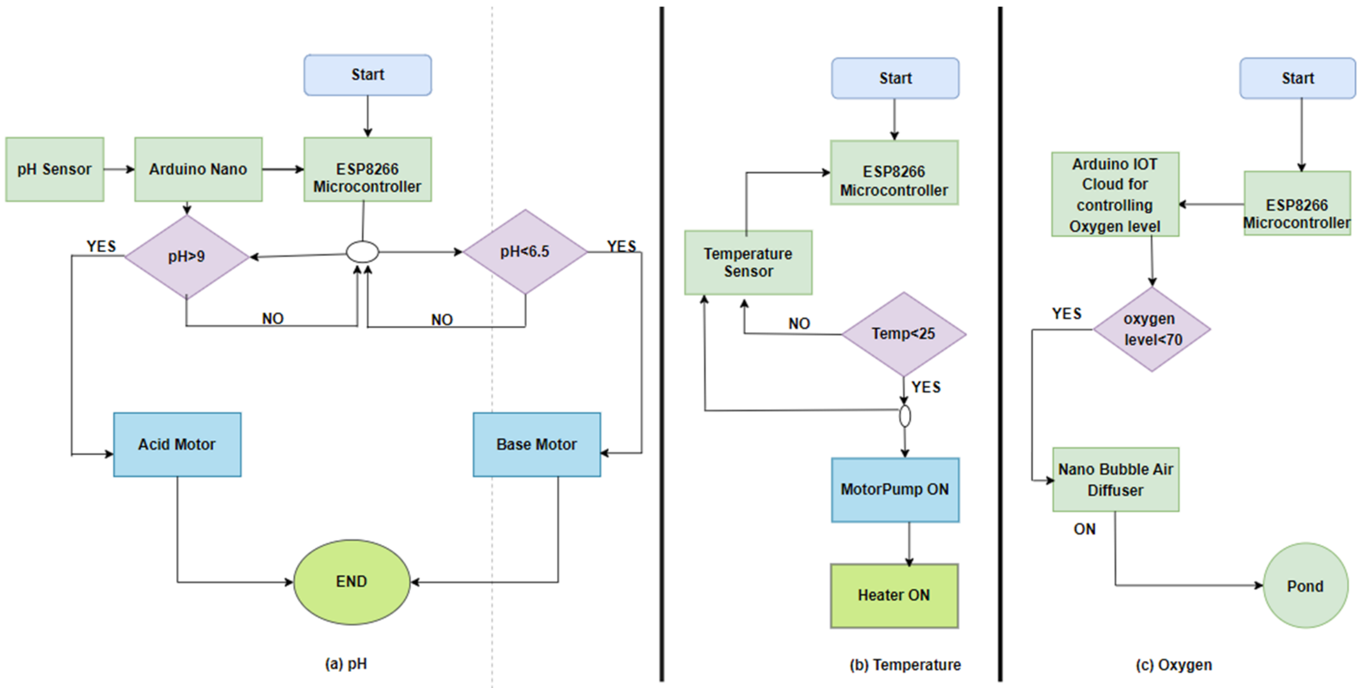

Figure 3. The working process of the proposed system.

Simultaneously, the system collects temperature data from two sensors to ensure data accuracy. This information is transmitted in real-time to the Arduino IoT cloud. It employs a temperature range of 22 °C to 27 °C for the accelerated growth of fish [25]. If the temperature exceeds this range, the system activates and continues until it achieves the threshold temperature.

To automate oxygen control, raw data are generated and sent to the Arduino IoT cloud. The system is configured to maintain the oxygen level at a threshold of 70. If the current oxygen level falls below this threshold, a nanobubble air diffuser is activated and remains operational until the threshold value is reached.

The methodology section of our study showcases a sophisticated approach to aquaculture management, emphasizing the significance of information management and data-driven technology in enhancing fish farming efficiency and sustainability. This approach integrates advanced IoT technologies with precise sensor data collection, enabling real-time monitoring and automated control over critical environmental parameters crucial for fish health and growth. Here is how information management and data-driven technology are highlighted within our methodology:

Information management through IoT integration: At the core of our system lies the integration of IoT technology, facilitating seamless data collection and transmission. By employing NodeMCU ESP-12E and Arduino Nano for connectivity and control, our system exemplifies how modern aquaculture can benefit from real-time data access and management. This IoT integration allows for the continuous monitoring of pH, temperature, and oxygen levels, pivotal for maintaining an optimal aquatic environment. The data collected are not only used for immediate adjustments but also stored in the cloud for historical analysis, demonstrating a comprehensive approach to information management.

Data-driven decision-making: The essence of our methodology is the transformation of raw sensor data into actionable insights. By employing algorithms and formulas to calculate and adjust pH levels, temperature, and oxygen content, our system operates on a data-driven basis. This includes the use of specific equations for temperature averaging, pH voltage calculation, and automated control mechanisms for heating, cooling, and oxygenation. Such precision underscores the data-driven nature of our system, where every decision and adjustment are based on accurate, real-time data, ensuring the well-being of the aquatic ecosystem.

Automated responses and remote monitoring: The implementation of automated responses to environmental changes represents a significant advancement in fish farming management. By setting thresholds for pH, temperature, and oxygen levels, our system autonomously adjusts these parameters, minimizing the need for manual intervention and reducing the risk of human error. This automation is underpinned by a sophisticated data analysis and management framework, allowing users to remotely monitor and control the system through a cloud-based interface. This not only improves operational efficiency but also ensures that fish farmers can maintain optimal conditions for fish growth from any location, at any time.

Enhancing operational efficiency and sustainability: our methodology leverages data-driven insights to optimize the fish farming process, significantly enhancing both operational efficiency and sustainability. By systematically analyzing sensor data, our system can predict and prevent undesirable conditions, leading to healthier fish populations and higher yields. This predictive capability, rooted in advanced data analytics, highlights the role of information management in achieving sustainable aquaculture practices.

In summary, our methodology exemplifies the integration of information management and data-driven technology in modern fish farming. By harnessing IoT capabilities for real-time monitoring, employing data-driven algorithms for environmental control, and enabling remote system management, it demonstrates a forward-thinking approach to aquaculture. This not only addresses the immediate challenges of fish farming but also sets a new standard for efficiency, sustainability, and scalability in the industry.

4. Experimental Results and Discussion

In Figure 4, a prototype of our proposed framework is presented. It focuses on automatically measuring and controlling key parameters such as pH, temperature, and oxygen levels, which are crucial for successful fish farming. These measurements are transmitted wirelessly to the Arduino IoT cloud server via the ESP8266 WIFI module embedded in the D1 microcontroller. Simultaneously, the data are stored in the cloud for future analysis.

Our proposed system sends the collected data to the Arduino IoT cloud-based web interface to create graphical visualizations. Figure 5 illustrates the pH data trends over time, and this information is stored in the cloud-based web server repository as a CSV datasheet for future analytics. Similarly, the system presents graphical representations of temperature data (Figure 6) and oxygen measurement data (Figure 7) for remote users.

This approach allows users to easily interpret and analyze the data trends in pH, temperature, and oxygen levels through visually intuitive graphs. The cloud-based storage ensures that the data are securely maintained for further analysis, providing a valuable resource for optimizing fish farming conditions and making informed decisions based on historical trends.

Based on the real-time graph analysis depicted in Figures 5–7, fluctuations are observed. These variations were intentionally induced by altering the environmental conditions to ensure the seamless testing of the system's automation accuracy. Furthermore, diverse time-related data were collected and subjected to graphical analysis, serving as a segue to the subsequent discussion.

As shown in Figures 6 and 7, we conducted extensive testing of the system by manually inputting a wide range of values. We closely monitored the resulting fluctuations in the data, which provided clear evidence of the system's ability to accurately capture and respond to these changes. This thorough testing process has demonstrated the reliability and effectiveness of the system in handling dynamic variations in parameters.

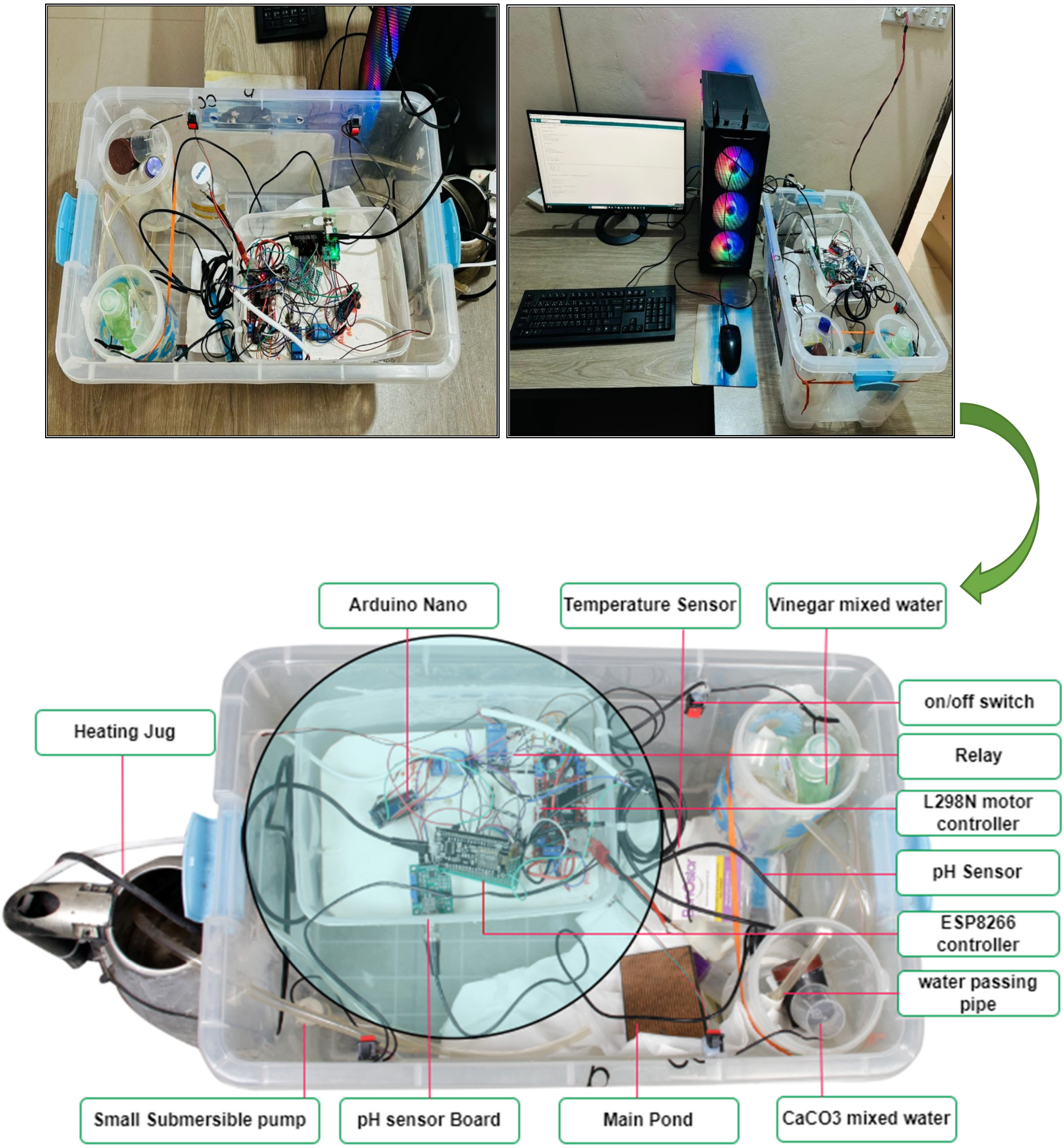

Figure 4. A photograph of the prototype.

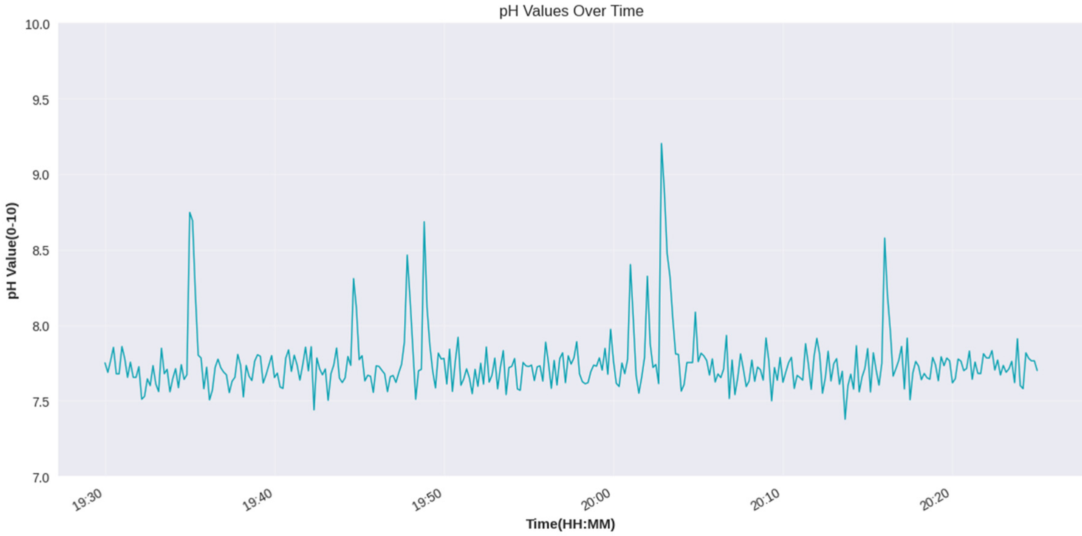

Figure 5. Real-time pH value observation.

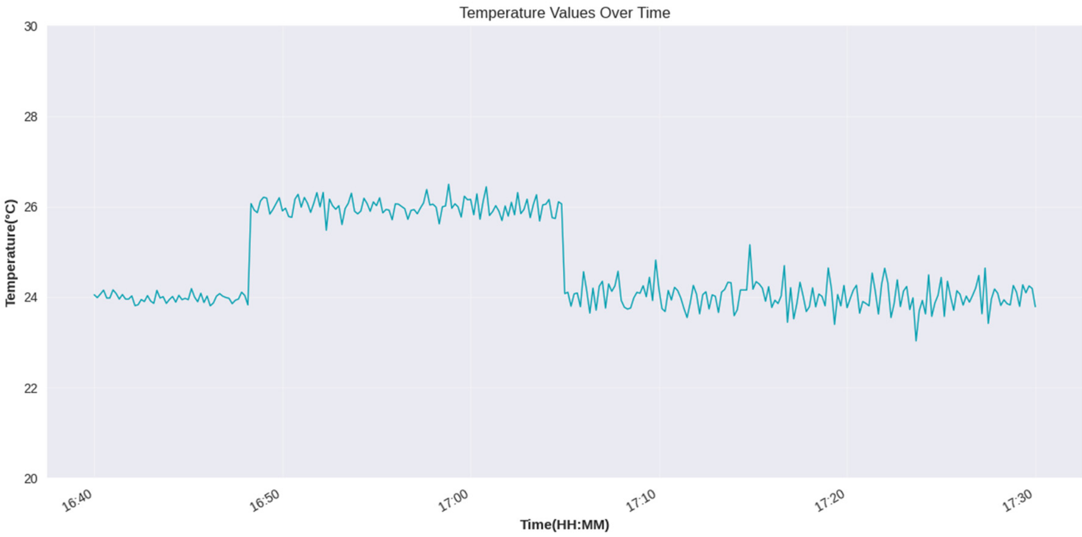

Figure 6. Real-time temperature value observation.

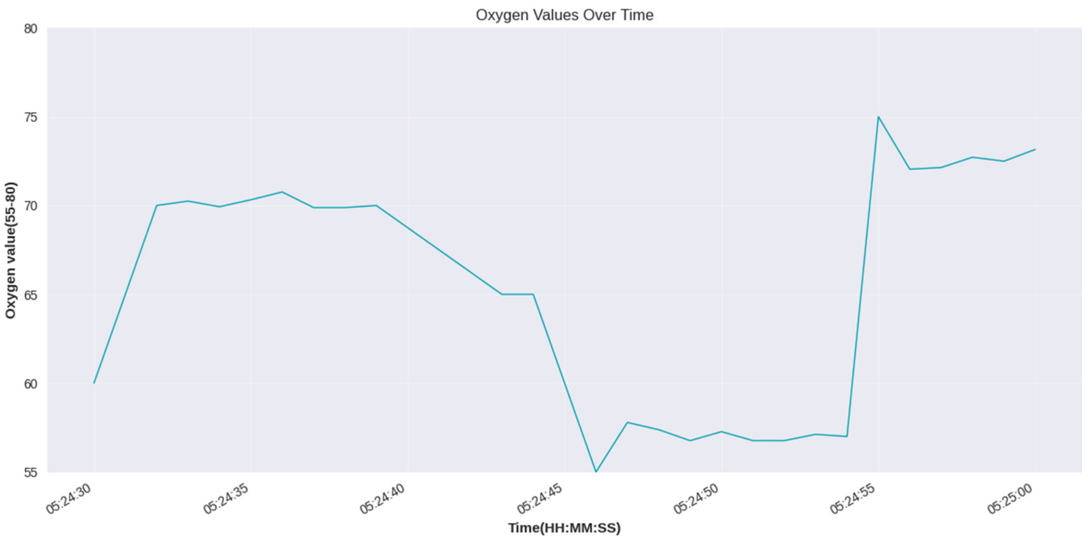

Figure 7. Real-time oxygen value observation.

Our system employs an intricate internal calculation methodology to analyze data received from various sensors. This involves a meticulous comparison of sensor readings with predefined reference values. The calculated data are then stored in multiple variables, facilitating a comprehensive presentation on the Internet. This internal calculation serves as the backbone for autonomous decision-making within the system.

The analyzed data revealed correlations between temperature fluctuations, pH levels, and oxygen content. These insights were interpreted to understand their implications on fish health and growth in intensive fish culture. Temperature variations were correlated with specific behavioral patterns in the fish population, while pH and oxygen levels were indicative of water quality, influencing aquatic life.

Critical Analysis of Fluctuations and Automation

In Figures 5–7, the graphical analysis highlights observable fluctuations in the measured parameters. These variations were intentionally induced by altering environmental conditions to validate the system's automation accuracy. While the system successfully responded to these fluctuations, maintaining stable conditions in real-world fish farming may require more precise control mechanisms. For instance, there could be delays in system activation or response time when thresholds are exceeded. Incorporating more advanced algorithms, such as machine learning, could help predict potential deviations and activate controls preemptively, improving the system's responsiveness.

Furthermore, the data analysis revealed correlations between temperature fluctuations, pH levels, and oxygen content. These insights shed light on the impact of these parameters on fish health and growth in intensive fish farming systems. Temperature fluctuations were linked to changes in fish behavior, while pH and oxygen levels provided indications of water quality, which in turn influenced aquatic life. However, this correlation could be further explored by integrating more long-term data to better understand seasonal and environmental impacts on fish farming.

4.1. Data Collection Strategy

Our research is predicated on the meticulous and systematic collection of pivotal data, crucial for the vigilant monitoring and adept management of the aquatic environment within our IoT-based automated fish farming system. Our data collection strategy is multifaceted, drawing upon specialized sensors, real-time data transmission, and a centralized dashboard for comprehensive visualization and in-depth analysis.

To facilitate this endeavor, we have employed the Tensilica L106 32-bit microcontroller (Tensilica Inc., Santa Clara, CA, USA), an exemplary choice for its remarkable specifications. With a generous complement of 27 GPIO pins and a capacious 4 MB memory, this microcontroller demonstrates its mettle by efficiently gathering data from temperature, pH, and oxygen sensors. The ESP8266 is a low-cost Wi-Fi module that integrates a Tensilica L106 32-bit microcontroller, making it capable of running applications and handling communication over Wi-Fi. The ESP8266 has gained popularity for its affordability and versatility in enabling Wi-Fi connectivity in various electronic projects and IoT (Internet of Things) applications. These data are judiciously stored as separate variables, as meticulously defined in our code analysis. One of the salient advantages lies in the microcontroller's power efficiency, drawing a mere 170 mA during active Wi-Fi transmission. This not only conserves energy but also enhances the longevity of our IoT-based system's operation. Moreover, the microcontroller's prodigious 160 MHz CPU clock frequency empowers it to swiftly and accurately collect real-time data from diverse sensors, ensuring the timely acquisition of critical information.

4.2. Sensor Deployment

The foundation of our data collection strategy is the strategic deployment of state-of-the-art sensors, each tailored to monitor specific parameters vital for the well-being of the aquatic ecosystem, and listed as follows:

DS18B20 Temperature Sensor: These sensors are meticulously placed within the fish bucket and water circulation systems at multiple depths. They continuously monitor temperature variations and fluctuations within the aquatic environment.

Atlas pH Sensor: Our system incorporates advanced pH sensors, carefully submerged in the fish tanks to enable real-time tracking of water acidity levels. These sensors provide precise pH measurements to ensure optimal pH conditions for fish health.

Oxygen generation and real-time monitoring: The system is designed to generate real-time data regarding oxygen levels through random data generation in the Arduino IoT cloud to continuously measure the dissolved oxygen content in the water, crucial for maintaining healthy fish populations.

4.3. Data Logging and Transmission

To ensure comprehensive data capture and real-time analysis, our IoT-based automated fish farming system employs a robust data logging and transmission mechanism:

Continuous data logging: All deployed sensors are equipped with data logging capabilities. Data readings are logged at frequent intervals; hot water passes from the pond for 20 s and waits 8 s at the heating jug to heat the water and the pump then starts to pass the water from the jug to the pond for 20 s. pH measurements are recorded every 1 min, and dissolved oxygen data are collected continuously. We have used two temperature sensors in this regard because when the heated water comes from the jug, it takes time to dissolve in the total water of the pond and for that reason, we have collected two sets of temperature reading data from two separate portions of the pond and measured average temperature to ensure data accuracy.

Real-time transmission: The collected data are transmitted in real-time to the Arduino IoT cloud dashboard. This seamless and continuous data transmission ensures that any deviations from predefined thresholds or unfavorable conditions are promptly detected and addressed.

4.4. Data Validation and Quality Assurance

In our relentless pursuit of data accuracy and reliability, we have instituted a rigorous regimen of data validation and quality assurance. At the heart of this process lies a commitment to upholding the highest standards of data integrity.

Sensor validation: Our dedication to precision leads us to conduct routine validation and calibration procedures for pH sensors. This procedure is executed meticulously to ensure that the data collected remain steadfast in their accuracy. Our pH sensor undergoes a meticulous calibration process using solutions of known pH levels, such as vinegar and calcium carbonate (CaCO3) mixed with water. Through these rigorous validations, we ascertain that our sensors consistently deliver dependable accurate data.

In Figure 8, the total calibration process of pH has several steps and in the very beginning, we measured pH in normal water and then in acidic water along with litmus testing several times, as shown in Figures 9 and 10.

Our journey towards accurate data collection has been marked by unwavering dedication and an unrelenting commitment to precision. We traversed a challenging path of research and development, leaving no stone unturned in our quest for data that could be deemed unquestionably accurate. This endeavor demanded tireless efforts, with days turning into weeks as we rigorously tested and retested our data collection mechanisms.

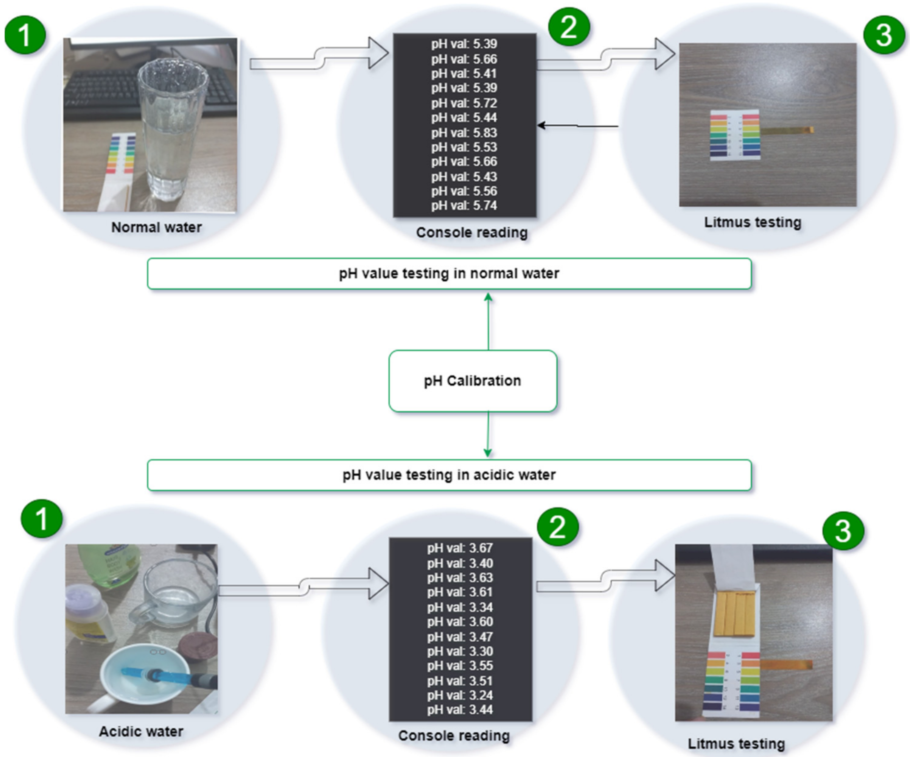

Figure 8. pH calibration steps.

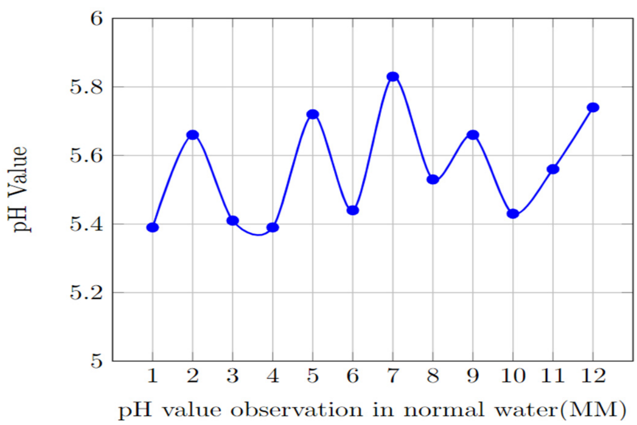

Figure 9. pH in normal water.

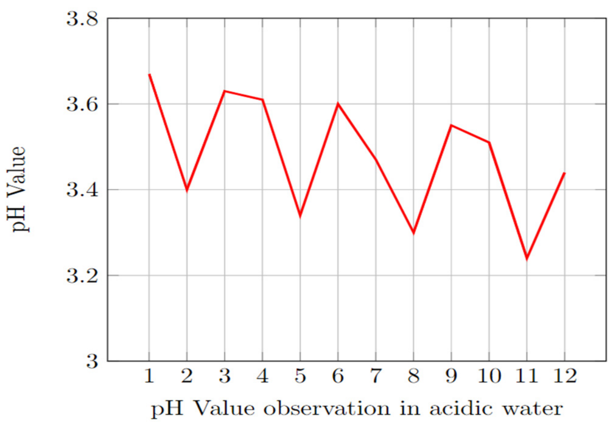

Figure 10. pH in acidic water.

Our relentless pursuit of precision reached its zenith when we attained the elusive pinnacle of accurate data. This milestone was not a mere happenstance, but the culmination of countless hours spent fine-tuning our temperature and pH sensors. These essential components underwent repeated calibration procedures, painstakingly executed, and meticulously refined. Our research journey stands as a testament to the rigorous pursuit of data accuracy, reflecting our unyielding commitment to excellence in every facet of our work.

4.5. Full Cycle of Data Collection

For remote monitoring, users can access a web-based interface on the Arduino IoT cloud, as shown in Figure 11. This interface allows end-users to examine real-time data, including the current readings and previous data analysis. If any parameter exceeds a predefined threshold, the system activates automatically and continues until the parameter returns to the acceptable range. This automated process minimizes the need for constant human intervention, enabling users to engage in cost-effective fish farming while ensuring optimal conditions for the aquatic environment. The provided system enhances efficiency and facilitates data-driven decision-making by offering a user-friendly interface for data analysis and control.

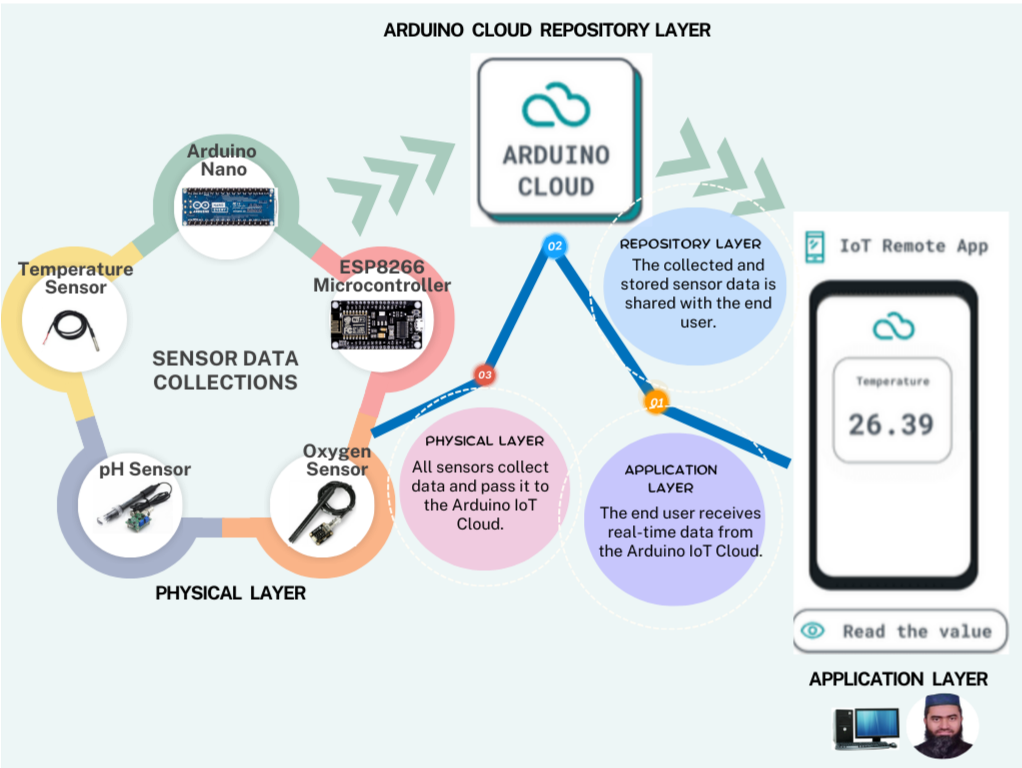

Figure 11. Total data cycle process in different stages.

In Figure 11, the total data collection process consists of several steps, primarily organized into three stages. In the first stage, the physical layer involves a direct connection of the Arduino Nano to the pH sensor. Additionally, the temperature and oxygen sensors are linked to the ESP8266 microcontroller, facilitating the direct transfer of data to the repository layer through the MQTT protocol. Lastly, at the application layer, the data are visualized using the Arduino IoT cloud.

4.6. Collected Sample Data Table of pH, Temperature, and Oxygen in Real-Time

We amassed extensive data across various time frames to meticulously assess the automation of our system, ensuring heightened precision. Our findings are exceptionally promising. Throughout this ongoing process, we systematically gathered data during morning, noon, evening, and night periods, focusing on pH, temperature, and oxygen levels. This comprehensive dataset enabled a thorough analysis, employing various types of graphical representations. The outcomes of these analyses distinctly affirm the system's reliability and accuracy with confidence.

The sample data collection illustrated in Table 1 and graph analysis indicate that the system redundancy and increases in accuracy, as per the graphs illustrated in Figures 12–14, fluctuate randomly, which was discussed earlier in Section 4.

Table 1. Sample data collection in the morning.

Sensor Name					
Time Frame	**pH (Value)**	**Time Frame**	**Temperature (Value)**	**Time Frame**	**Oxygen (Value)**
7:40:28	7.75	7:40:28	30.75	6:15:07	70
7:40:28	7.75	7:40:31	30.78	6:16:07	72
7:40:31	7.78	7:40:57	30.75	6:17:07	67
7:40:57	7.75	7:41:00	30.78	6:18:07	70
7:41:00	7.78	7:41:03	30.75	6:19:07	69
7:41:03	7.78	7:41:05	30.78	6:20:07	71
7:41:05	8.28	7:43:47	30.28	6:21:07	70
7:43:50	8.31	7:43:50	29.31	6:22:07	71
7:43:47	8.28	7:43:53	28.78	6:23:07	69
7:43:53	8.78	7:43:58	26.75	6:24:07	70

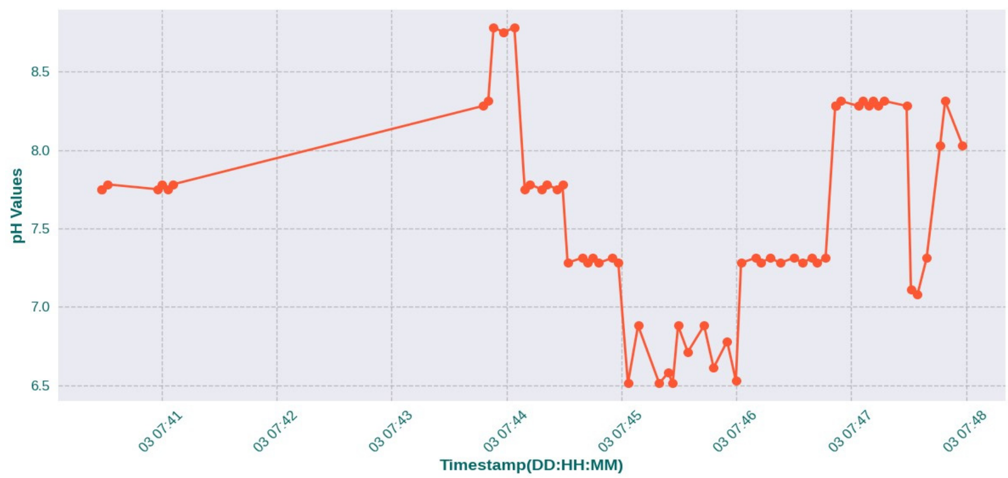

Figure 12. Morning pH value observation.

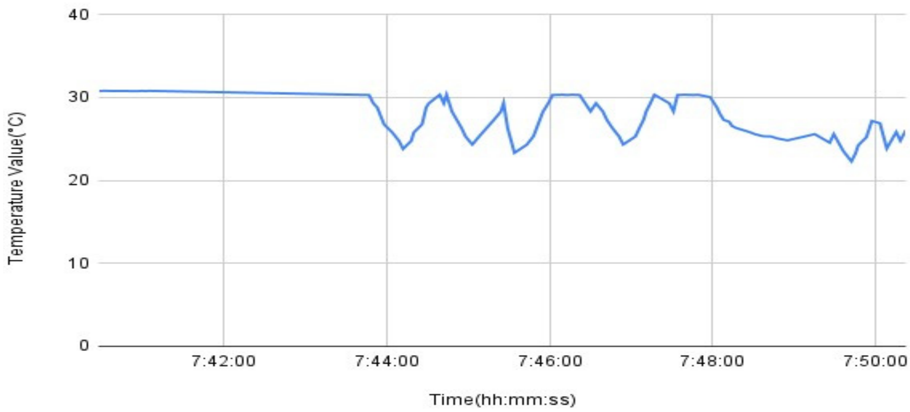

Figure 13. Morning temperature value observation.

Figure 14. Morning oxygen value observation.

The sample data collection illustrated in Table 2 and graph analysis indicate that the system redundancy and increases in accuracy, as per the graph illustrated in Figures 15–17, fluctuate randomly, which was discussed earlier in Section 4.

Table 2. Sample data collection at noon.

Sensor Name					
Time Frame	**pH (Value)**	**Time Frame**	**Temperature (Value)**	**Time Frame**	**Oxygen (Value)**
13:18:44	6:43:12	13:18:00	24.84	14:35:07	70
13:18:47	7:26:24	13:18:00	25.03	14:36:07	71
13:18:49	6:43:12	13:18:00	25.25	14:37:07	67
13:18:52	7:26:24	13:18:00	25.43	14:38:07	70
13:18:55	6:43:12	13:18:00	25.62	14:39:07	69
13:18:58	7:26:24	13:18:00	25.78	14:40:07	68
13:19:01	6:43:12	13:19:00	25.93	14:41:07	70
13:19:04	7:26:24	13:19:00	26	14:42:07	70
13:19:06	6:43:12	13:19:00	26.18	14:43:07	68
13:19:09	7:26:24	13:19:00	26.31	14:44:07	70

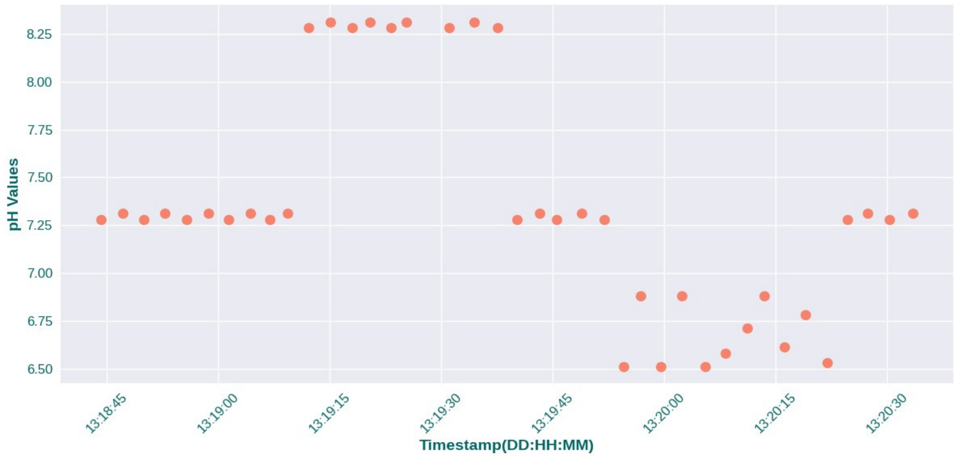

Figure 15. pH value observation at noon.

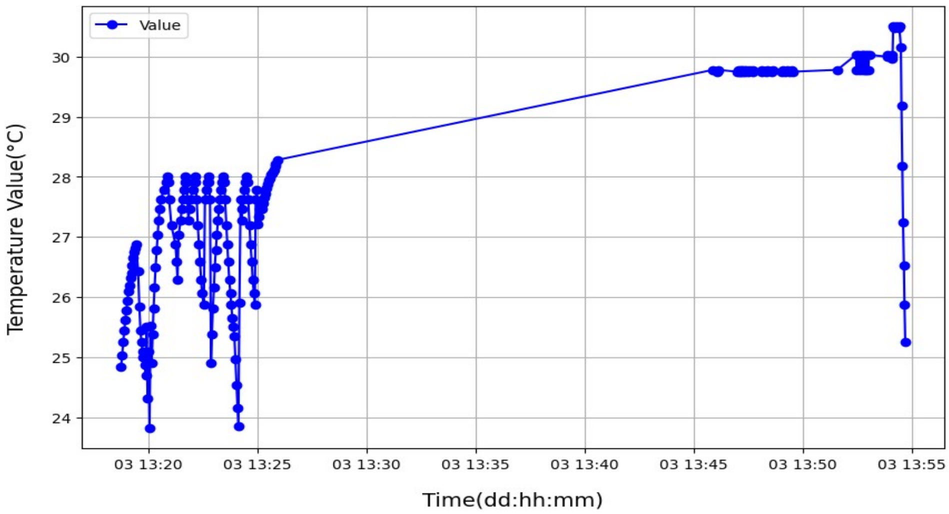

Figure 16. Temperature value observation at noon.

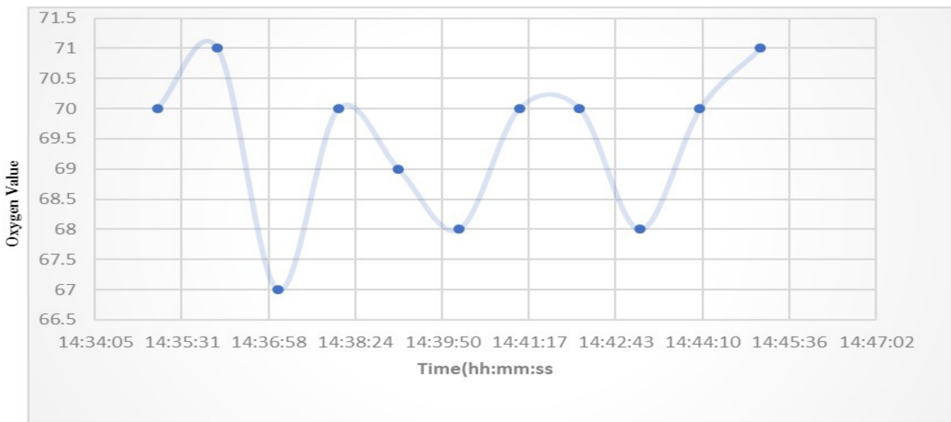

Figure 17. Oxygen value observation at noon.

The sample data collection illustrated in Table 3 and graph analysis indicate that the system redundancy and increases in accuracy, as per the graph illustrated in Figures 18–20, fluctuate randomly, which was discussed earlier in Section 4.

Table 3. Sample data collection in the evening.

Sensor Name					
Time Frame	**pH (Value)**	**Time Frame**	**Temperature (Value)**	**Time Frame**	**Oxygen (Value)**
19:58	7.28	19:57:00	30.67	20:15:07	70
19:58	7.31	19:58:00	30.65	20:16:07	65
19:59	7.28	19:59:00	30.06	20:17:07	67
19:59	7.31	20:00:00	29.37	20:18:07	70
19:59	8.28	20:01:00	28.75	20:19:07	69
19:59	8.31	20:02:00	28.28	20:20:07	50
19:59	8.28	20:03:00	28.21	20:21:07	70
19:59	8.31	20:04:00	28.4	20:22:07	65

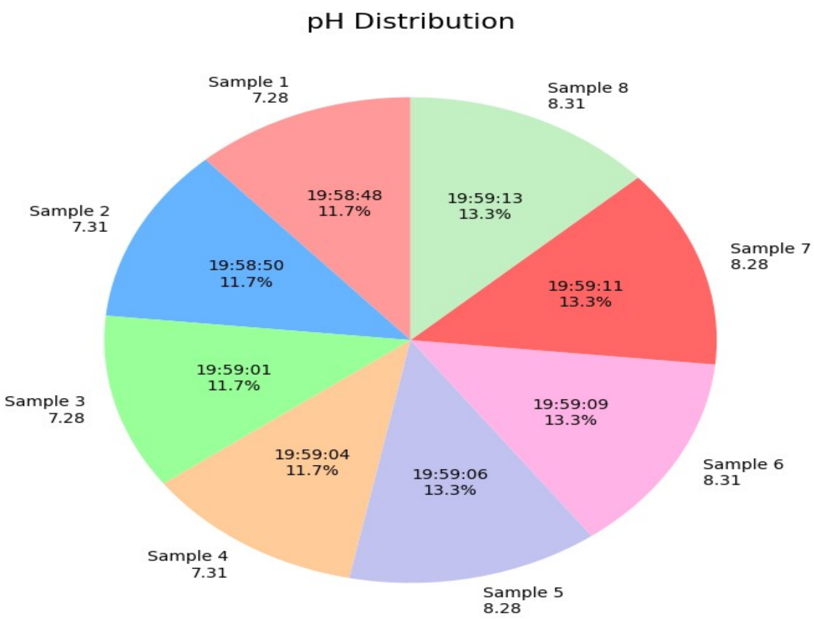

Figure 18. pH value observation in the evening.

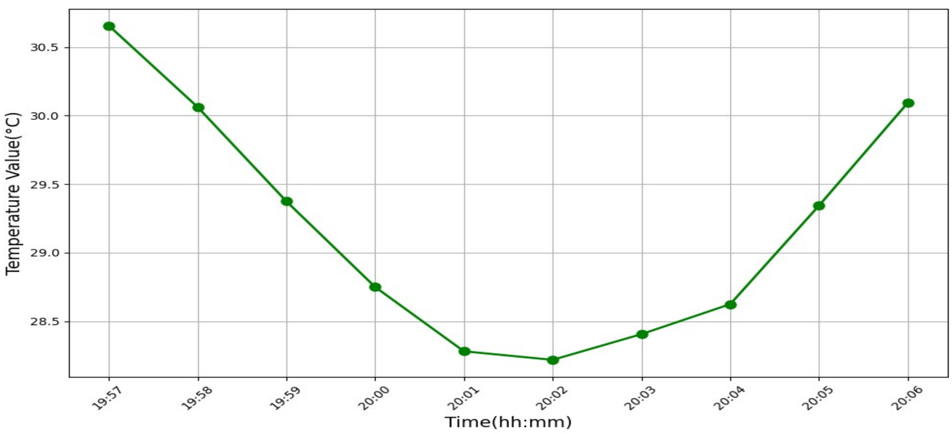

Figure 19. Temperature value observation in the evening.

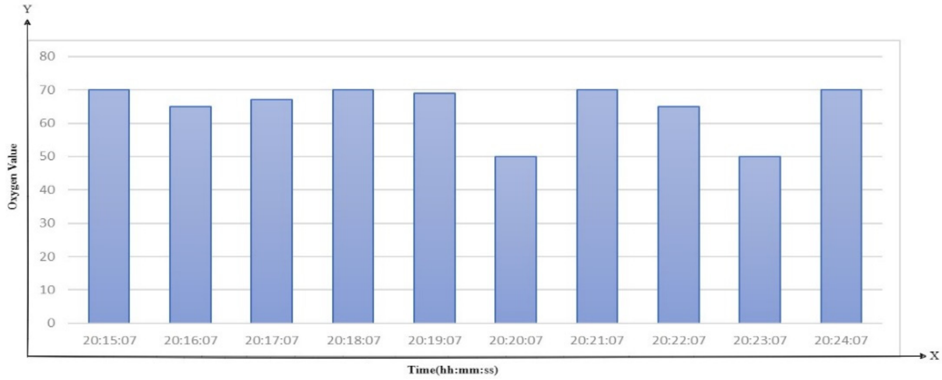

Figure 20. Oxygen value observation in the evening.

The sample data collection illustrated in Table 4 and graph analysis indicate that the system redundancy and increases in accuracy, as per the graph illustrated in Figures 21–23, fluctuate randomly, which was discussed earlier in Section 4.

Table 4. Sample data collection at night.

		Sensor Name			
Time Frame	**pH (Value)**	**Time Frame**	**Temperature (Value)**	**Time Frame**	**Oxygen (Value)**
23:36:11	7.28125	23:33:00	26.96	23:20:07	70
23:36:16	7.3125	23:33:00	26.96	23:21:07	65
23:36:19	7.28125	23:33:00	25	23:22:07	67
23:36:21	7.3125	23:33:00	24.75	23:23:07	70
23:36:24	8.28125	23:33:00	25	23:24:07	69
23:36:29	8.3125	23:33:00	27.03	23:25:07	50
23:36:32	8.28125	23:33:00	26.78	23:26:07	70
23:36:35	8.3125	23:33:00	26.78	23:27:07	71

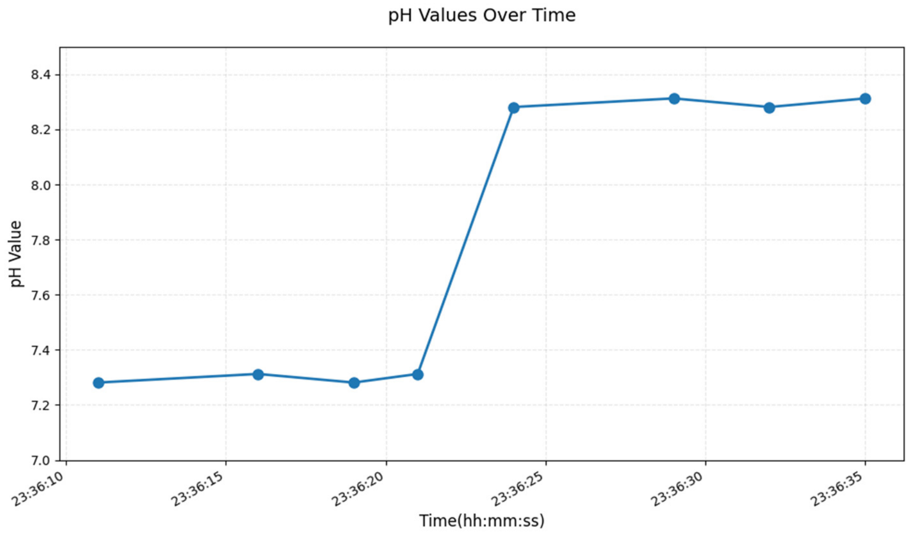

Figure 21. pH value observation at night.

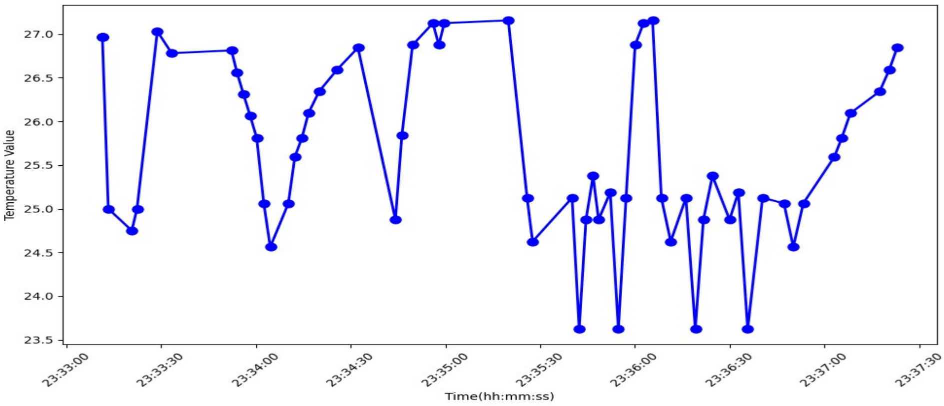

Figure 22. Temperature value observation at night.

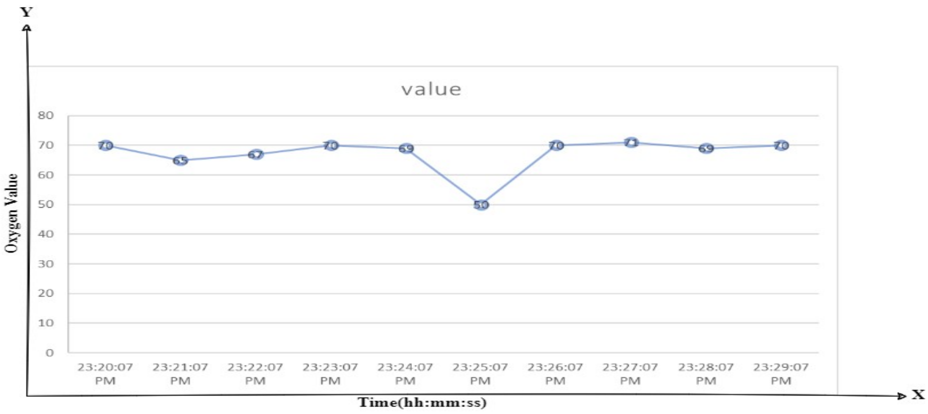

Figure 23. Oxygen value observation at night.

The system's precision and accuracy are guaranteed through the comprehensive collection of raw data from various sensors. Analysis through the graphical representation of data over different time frames for pH, temperature, and oxygen sensors further refines and validates the system's performance. Each analysis is conducted in real-time, ensuring that the system operates with high accuracy.

The graphical representations serve as a visual verification, allowing users to quickly assess the system's performance at a glance. The absence of errors, indicated by a zero-percentage error, is affirmed by the consistency and reliability of the real-time data collections and their corresponding graphical analysis. This approach enhances the system's credibility and assures users of its capability to provide precise and dependable information for effective monitoring and control.

Our system exemplifies advanced information management by efficiently collecting, transmitting, and analyzing sensor data to ensure optimal fish farming conditions. The use of the NodeMcu12E ESP8266 microcontroller and integration with the Arduino IoT cloud facilitates real-time data management and supports decision-making processes that are critical for maintaining the health and growth of fish populations.

Security and data privacy: MQTT (Message Queuing Telemetry Transport) is used for securely transmitting temperature and pH sensor data from the ESP8266-12E to the IoT cloud. In our IoT-based system, we have harnessed the power of MQTT, an efficient and lightweight protocol tailored for Internet of Things (IoT) communication. MQTT offers a robust solution for secure data transmission, combining speed and reliability with built-in security features. With MQTT, our ESP8266-12E microcontroller seamlessly connects to the Arduino IoT cloud, establishing a secure channel for data exchange. This protocol supports TLS/SSL encryption, guaranteeing that the temperature and pH sensor data remain confidential and tamper-proof during transit. MQTT's pub–sub (publish–subscribe) architecture ensures that data are efficiently delivered to the cloud, reducing latency and conserving valuable resources. By adopting MQTT, we have fortified our data transmission with the highest standards of security and efficiency, setting the stage for accurate and reliable data collection and analysis in our IoT-based fish farming research.

Data validation and quality assurance: Rigorous data validation procedures, including sensor calibration and real-time data verification, highlight the system's focus on data accuracy and reliability. These practices ensure that the information used for decision-making is both precise and dependable.

Update online: The system provides real-time updates of all measured parameters online. Users can access this information instantly, enabling them to make informed decisions promptly. The seamless flow of data from the sensors to the cloud ensures that users have access to the most recent and accurate information. The heart of our data collection strategy is the integration with the Arduino IoT cloud platform.

Centralized data repository: A centralized data repository plays a pivotal role in our data management strategy. All data meticulously collected from our array of sensors find their rightful place within the secure confines of the Arduino IoT cloud. Here, they converge to create a harmonious and unified ecosystem that serves as a centralized repository, dedicated to the storage, adept management, and real-time visualization of these invaluable data. One notable advantage of this repository is its accessibility. Should the need arise for a deeper dive into historical data or specialized analysis, our system offers the convenience of downloading stored data in popular formats like Excel or CSV. This feature facilitates seamless data extraction, enabling further exploration and in-depth examination, all while preserving the integrity and accuracy of the original data. Our centralized data repository within the Arduino IoT cloud not only safeguards the treasure trove of data but also empowers us with the flexibility to extract and manipulate data as required, ensuring that our research endeavors remain at the forefront of precision and insight.

Dashboard visualization: Our proposed model design boasts a sophisticated feature set that culminates in the illuminating dashboard visualization. This element of our system architecture shines as a beacon of insight and user-friendliness. With our meticulous data collection processes ensuring accuracy and reliability, the culmination of these data is expertly presented on the Arduino IoT cloud dashboard. This dashboard is not merely a display; it is a user-friendly interface designed to empower users with real-time insights. Here, the data collected from various sensors, including temperature, pH, and dissolved oxygen, are harmoniously presented in a cohesive and visually intuitive manner. Users, whether they be aquaculture experts or novices, are granted immediate access to this rich tapestry of information. It elevates the management of the aquatic environment to new heights, ensuring the well-being of aquatic life and the success of our research endeavors. Our system will update all the data online in real time. Users can view this and make multiple decisions based on it.

Scalability and accessibility: By leveraging cloud-based technologies and IoT innovations, our system presents a scalable solution that enhances the accessibility of data. This not only addresses the operational needs of fish farming but also contributes to broader goals of sustainable food production through efficient resource management.

In summary, our research showcases a sophisticated integration of sensor technology, information management, and data-driven strategies. This approach not only enhances the efficiency and sustainability of fish farming operations but also provides a scalable model that can be adapted to meet the growing global demand for protein.

5. Conclusions

The conclusion of this study underscores the pivotal role of information management and data-driven methodologies in modern aquaculture, specifically through the innovative application of an IoT-based smart fish monitoring and control system. This system, by harnessing continuous, real-time sensor data on critical water quality parameters such as pH, temperature, and oxygen levels, offers a transformative approach to fish farming. The integration of these data points to the Arduino IoT cloud elevating the capacity for remote monitoring and control, enabling fish farmers to manage their operations with unprecedented precision and efficiency from any global location. This real-time data collection and analysis not only facilitates immediate adjustments to the aquatic environment but also provides a wealth of historical data for predictive analytics and strategic planning. Such a robust information management framework ensures optimal fish growth conditions, minimizes risks, and significantly reduces the need for manual intervention. To strengthen future research, we recommend exploring the integration of machine learning algorithms for advanced predictive analytics, which can assess fish well-being and health, further revolutionizing fish farming practices. Additionally, field studies involving diverse fish species and varying environmental conditions could provide deeper insights into the system's versatility and effectiveness. For commercial applications, developing user-friendly mobile applications could enhance accessibility for farmers, enabling them to monitor their operations on the go. Partnerships with aquaculture companies could facilitate pilot programs to validate the system's efficacy in real-world scenarios, paving the way for broader adoption. By leveraging data-driven insights to optimize production processes, this IoT-based system directly contributes to addressing the critical global challenge of increasing protein supply. It stands as a testament to the potential of integrating technology and data management in sustainable food production, offering a scalable and economically viable solution that aligns with the pressing demands of global food security.

The following list summarizes the contributions of this paper:

1. This study addresses the implementation of an IoT-based system utilizing the NodeMcu12E ESP8266 microcontroller for automated management of critical water quality parameters in fish farming, specifically focusing on monitoring pH, temperature, and oxygen levels.
2. This study proposes the integration of an Arduino IoT cloud-based framework, offering a user-friendly web interface for the remote monitoring and management of fish farming operations from any global location.
3. This study demonstrates the optimization of fish growth conditions and the reduction in mortality rates through an intelligent monitoring and control mechanism.
4. This research depicts the reduction in risks associated with manual monitoring and adjustments in fish farming operations, achieved through the persistent autonomous functionality of the system.
5. By leveraging data-driven technologies and IoT innovations, the study addresses the immediate needs of the fish farming industry while contributing to the broader global challenges of protein production, offering a scalable and accessible approach to modern aquaculture for maximizing output and minimizing risks.

Author Contributions: Conceptualization, S.A.H. and K.M.R.; Software, M.N.I.N.; Formal analysis, T.J.; Investigation, K.N.e.A.S.; Resources, T.J.; Data curation, M.S.I.; Writing—original draft, M.N.I.N.; Writing—review & editing, K.M.R.; Supervision, S.A.H. and K.M.R.; Project administration, K.N.e.A.S.; Funding acquisition, M.S.I. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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