AQUA GUARD

SMART WATER QUALITY MONITORING FOR AQUACULTURE

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Document: Aqua Guard (Smart Water Quality Monitoring for Aquaculture)

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Abstract

Aquaculture has an important role to play in the world's food production, but it poses a challenge to the ability to maintain water quality, as this has a direct impact on the health, growth, and survival of aquatic organisms. Conventional methods for monitoring water parameters can often be labor-intensive, time-consuming, and lack real-time knowledge. This project proposes and develops an IoT-based smart water quality monitoring system for aquaculture applications, which aims to overcome this problem by allowing for real-time, remote, and continuous monitoring of water parameters.

The system includes a variety of sensors, including pH, temperature, dissolved oxygen (DO), and turbidity sensors that connect to a microcontroller (Arduino) that collects and sends information to the cloud via wireless communication protocols. The cloud-based data can be visualized in an easy-to-use interface that allows aquaculture managers to see live conditions of their farms and receive alerts if certain parameters are outside of acceptable ranges. The design leverages cost-effective, scalable, and deployable technologies to maximize the availability and uptake of new technologies for small and medium-sized fish farms.

Key objectives of this project included: designing a complete hardware and software architecture for the system, implementing real-time data acquisition and remote monitoring capabilities; and assessing the system's performance in a controlled aquaculture environment. As a multiparty system, the approach comprised experimental prototyping and testing in the field to assess the system's accuracy, reliability, and responsiveness as an IoT system.

The results showed that the system was able to monitor water quality parameters in real time with an acceptable latency and with reliable data communications. Alarms were successfully triggered under abnormal conditions, enabling discrete interventions. This project also highlighted the operational requirements for calibration of sensors, power management, and having an established and stable network for long-term performance in an operational environment.

Acknowledgement

I would like to express my deepest gratitude to my supervisor, Mr. R.M.C. Rathnayaka (Engineer/Access Network Planning/SLT), for his invaluable guidance, constructive feedback, and continuous encouragement throughout the development of this project. His expertise and support have been instrumental in shaping the Aqua Guard system from concept to completion.

I am also sincerely thankful to the Pearson BTEC programme coordinators and lecturers of the Higher National Diploma in Digital Technologies for providing the knowledge base and resources that made this work possible.

Special appreciation goes to the aquaculture farmers and industry professionals who shared their insights, offered practical feedback, and helped in testing the system in real-world conditions. Their cooperation provided vital perspectives that enhanced the practicality and relevance of this project.

Finally, I am grateful to my family and friends for their unwavering moral support, patience, and encouragement during the entire research and development process. Without their understanding and motivation, this project would not have reached its current level of success.

Thank you all for your support and encouragement.

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1. Introduction

1.1. What is Emerging Technology?

Emerging technology encompasses novel devices, systems, or practices that are still in their infancy but can greatly impact the marketplace, society, and everyday life. Emerging technologies are characterized by fast speed, high impact, and the ability to develop new opportunities or come up with better solutions to existing problems. Emerging technologies include the Internet of Things (IoT), artificial intelligence (AI), cloud computing, and blockchain. IoT and cloud-based monitoring are emerging technologies and can be considered emerging technologies in the context of this project because IoT and cloud-based monitoring are modern technologies that automate, use real-time monitoring, and create data-driven decisions, which improve conventional aquaculture practices.

1.2. Research Questions

- How can IoT and the Blynk app be used to develop a user-friendly, efficient, and cost-effective smart water quality monitoring system for aquaculture?
- How can the system be designed to function effectively in areas with limited or unreliable internet connectivity?

1.3. Objectives

- Identify appropriate IoT sensors for parameters, dry temperature, dissolved oxygen, and turbidity.
- Physical wireless communication networking, to ensure data transference.
- Develop data storage, processing, and visualisation of data through a cloud platform.
- Create a mobile application for monitoring and assessing the sensing data.
- The evaluation of the performance of the system depended on realistic data mining under aquaculture ecosystems.

1.4. Methods

We used a mixed methods approach in this study by combining experimental design, simulations, and interviews. We manufactured hardware and developed software systems, and these were studied in confined spaces to test their reliability and validity. Our data capture processes were augmented with real-time IoT sensors that collected quantitative data and behaved like actual performance. User feedback (qualitative data) contributed to our understanding of the effectiveness and usability of the technologies we were assessing.

1.5. Importance of Research Findings

The research outcomes will help advance sustainable aquaculture practices by finally enabling real-time monitoring of water quality. Knowing when the environmental parameters of an aquaculture system are compromised allows actions to take place which can salvage fish health and optimize productivity. The approach will help reduce negative environmental impacts of aquaculture such as pollution and habitat loss by enabling the appropriate actions to be undertaken in the moment when they are required. The benefits of the research and development will include an increase in fish farming productivity, a cost savings for fish producers, and hopefully is the next step in the evolution of technology in aquaculture.

2. Literature Review

2.1. Historical Evolution of IoT in Water Quality Monitoring

Water quality monitoring has evolved from an entirely manual sampling methodology to a fully automated, real-time IoT-enabled approach. Traditionally, water quality was assessed based on manual sampling and laboratory analysis, which was not only time-consuming, but it did not provide immediate water quality results. In aquaculture, this delay in information often causes management to take too long to respond to the water quality issue, subsequently decreasing the potential productivity or mortality of fish.

In the early 2000s, electronic sensing devices were developed to continuously monitor various parameters in the environment (pH, temperature, dissolved oxygen). Although these instruments were a step up from traditional methods, they were non-integrated systems that stored collected data on the instrument, requiring users to physically retrieve the data from the instrument, and thereby limiting their effectiveness for large-scale, remote monitoring.

There was a pivotal year around 2005, when wireless sensor networks (WSNs) were integrated into systems that carried out the required data transmission, without any human interactions. The introduction of WSN systems started to be integrated into environmental projects. This, and many of the early examples, were in aquaculture projects, where multiple sensor nodes could transmit data to a single station (Akyildiz *et al.*, 2002)

Starting around 2010, the growth of the Internet of Things (IoT) ecosystem has fundamentally changed atmospheric water quality monitoring. Base microcontrollers like Arduino and Raspberry Pi, combined with low-power wireless communication protocols (e.g., LoRaWAN, Zigbee, and later NB-IoT, which gave us range, low power consumption, and metastable network capacity), homogenized avenues of sensor networks that could be deployed at comprehensive scales of spatial data collection in both freshwater and marine systems. These systems can provide low-cost, continuous, automated, real-time monitoring capabilities with immediate actionable data and outcomes to aquaculture practitioners.

Recently, IoT-based water quality monitoring systems have progressed to smart, connected cloud-based systems that use machine learning and predictive analytics to monitor the water conditions and take preventive action before water conditions fail. Additionally, farmers and environmental organizations can monitor and compare multiple locations from anywhere with the use of mobile applications, enhancing their decision-making processes.(Rashid *et al.*, 2021)

2.1. Review of Similar Studies

Adnan Sarwar and M.Tariq Iqbal (2024)

The authors, Adnan Salwar and M. Tariq Iqbal, cover the use of IoT-based real-time health monitoring systems in aquaculture in their 2024 article. The article presents various technologies that can be used to address the challenges faced by aquaculture producers in modern aquaculture. To enhance production efficiency and sustainability, the authors investigate new approaches and a range of methods. The authors harness the potential of the Internet of Things (IoT) to take a system-wide approach to health diagnosis, environmental conditions, and quality improvements in aquaculture. Through this contribution, Sarwar and Iqbal provide an illustration to demonstrate how such technology can transform traditional aquaculture practices into an agile and resilient food production system.

Objective

Sarwar and Iqbal's venture aims to develop an innovative and advanced real-time monitoring system to enhance the health of aquaculture systems. Their solution is expected to fundamentally and dramatically improve the sustainability of the aquaculture industry and the efficiency with which aquaculture producers grow fish. With this solution, we have reached a point where we can implement advanced Internet of Things (IoT) systems to automate water quality monitoring, facilitating smart, precise, and timely interventions that produce healthier aquatic ecosystems and ultimately lead to increased production. From a process perspective, the approach is also going to streamline the process on behalf of aquaculture producers while also enabling producers to rely on and verify environmental standards through responsible aquaculture.

Methodology

This study combines advanced sensors, microcontrollers, and Internet of Things (IoT) platforms to systematically gather and monitor critical water quality parameters, including temperature, pH levels, and dissolved oxygen content. By interlinking these components, the system facilitates real-time data transmission, empowering aquaculture practitioners to make timely and informed decisions that can significantly enhance their operations. The methodology focuses on automation and continuous monitoring, which minimizes the need for manual interventions and improves overall efficiency in water quality management.

Findings

The study shows that the Internet of Things (IoT)-enabled system significantly improves operational efficiencies within aquaculture. This system improves operational efficiencies through the automation of data collection and analysis. All operational efficiencies result in increased sustainability by better resource management, decreasing waste, and increasing the overall productivity with a lower negative environmental impact. The real-time monitoring also provides timely information regarding potential problems, and operators can respond quickly to keep the conditions as ideal as possible for the health and growth of aquatic animal or marine animal life.

Comparison with Aqua Guard

There are significant similarities between the project designed by Sarwar and Iqbal and Aqua Guard, especially in their use of IoT technologies for the measurement of various parameters related to water quality in real time. Aqua Guard, however, improves on this aspect with predictive analytics based on machine learning. Consequently, Aqua Guard not only measures parameters but also predicts water quality, providing users with information about likely future scenarios. Furthermore, Aqua Guard has a built-in turbidity monitor that provides a thorough analysis of clear water. Additionally, it features a user-friendly mobile application that allows users to easily monitor and manage their accounts from a distance, keeping them up to date with crucial information from any location. These particular aspects of Aqua Guard's features are not articulated in Sarwar and Iqbal's project, indicating a gap in their line of inquiry for water quality monitoring.

(*View of IoT-Based Real-Time Aquaculture Health Monitoring System*, no date)

Krishna Reddy (2022)

In 2022, Krishna Reddy published research on employing IoT technology to advance the monitoring of water quality in smart aquaculture. This publication examines the need for a smart aquaculture system that may aid in mitigating the major concerns of being able to manage adequate water quality conditions, which are fundamental for aquaculture systems. Discussing multiple aspects of IoT, the study addresses the role of real-time applications for receiving and analyzing data and developing monitoring protocols for adoption, and provides evidence of how new technology and IoT can enhance aquaculture practices. Conclusively, Reddy discusses options for IoT applications to produce better aquatic environments for aquaculture systems instead of becoming more productive and sustainable.

Objective

The primary aim of Reddy's project is to build an IoT-enabled system to monitor important water quality indicators in aquaculture. The purpose of this new system is to promote water quality management by providing real-time information about a variety of critical indicators, including temperature, pH, dissolved oxygen, and turbidity. The IoT-enabled system allows aquaculture users to manage their liveries remotely, allowing them to make timely, informed decisions and effectively address problems that may arise. This system leads to healthy aquatic ecosystems and increased sustainability in fish farming.

Methodology

Reddy's innovative solution is built around the power of IoT sensors to carefully measure key water quality indicators such as pH, temperature, and dissolved oxygen. These sensors are integrated with a reliable IoT platform to efficiently relay data to a central system for processing and analysis. The system puts an emphasis on real-time measurements so users can monitor water quality conditions anywhere. Being able to access the health of a water source remotely is impactful for quick-to-act users.

Findings

This research highlights the significant advancements in water quality management due to the utilization of Internet of Things (IoT) technology. By enabling real-time monitoring of water quality parameters, this technology allows any anomalies or water quality deterioration to be detected immediately. This allows stakeholders to take timely actions to mitigate potentially harmful effects to the aquatic environment. The remote access technology further enhances user convenience, allowing for efficient operations and the proactive management of water resources. This enabling technology allows users to monitor and respond to water quality issues from almost any location, which is a further optimization of the management strategy.

Comparison with Aqua Guard

Reddy's work is similar to Aqua Guard in its focus on real-time monitoring and its application of IoT sensors to monitor current water quality measurements of interest to scientists and engineers (e.g, pH, temperature, and dissolved oxygen). However, the initiatives have significant differences.

- Aqua Guard's turbidity monitoring is one of its most notable features. This allows the overall assessment of water quality to be examined through the clarity of the water, broadening the understanding of possible contaminants and pollutants.

- Aqua Guard leverages sophisticated machine learning algorithms to conduct predictive analytics. This functionality is important because it enables the pre-emptive discovery of potential water quality challenges so that proactive management and intervention can take place before issues deteriorate.

- With users in mind, the Aqua Guard system incorporates a mobile application that is designed for ease of use and is focused on user experience. Reddy's project, on the other hand, focuses on merely providing basic remote access, possibly limiting user engagement and real-time responsivity in comparison to the Aqua Guard system's more comprehensive possible solutions.

(Kanwal *et al.*, 2024), (Parra *et al.*, 2018), (Azeem Ganusha Kkavya Anjali Chlakshmi Sravani, 2024)

Ganapati S.P Kumar (2018)

Ganapati S.P. Kumar's 2018 research paper, "E-Aquaculture Monitoring Using Internet of Things," investigates IoT's creative extensions in aquaculture, including the real-time monitoring of water and soil conditions. This work provides a robust overview of the ways the IoT can support how aquaculture is managed and sustained by providing data related to a number of environmental parameters. This paper provides discussions of procedures, technologies, and possible positive consequences of integrating IoT systems into aquaculture. The research focuses on the most significant components of aquaculture, such as water quality, soil health, and predator/prey ratios, to express the ways IoT solutions are changing aquaculture management and enabling more effective operations.

Objective

This research study aimed to demonstrate the promise of using IoT technologies to transform aquaculture practices through the automation of monitoring water and soil quality. Even in less developed countries, with sensors and real-time analytics available at their disposal, agricultural managers can minimize the human labour required and make operations more efficient and accurate. Furthermore, utilizing IoT can lead to the possible implementation of more sustainable practices that prioritize the health of surrounding aquatic ecosystems. All in all, the study established a preliminary commitment to technology as the driving force in realizing a more environmentally sound aquaculture practice.

Methodology

Kumar has designed a multi-faceted sensor network, including pH, humidity, water level and oxygen sensors, all connected to IoT platforms to collect real-time data from multiple aquaculture locations. This complicated and nuanced system not only allowed for the real-time transmission of sensor readings from each aquaculture location to one analytic system for thorough investigation and interpretation of data, but it also made continuous monitoring of important parameters critical for the health and welfare of aquatic life possible.

Findings

The study highlighted how the Internet of Things (IoT) could transform the aquaculture sector by:

- Providing real-time information on the intricate interactions of water quality and soil conditions that aquaculture operators can respond to immediately, allowing them to manage the environment as optimally as possible.
- Reducing labor costs in aquaculture through automated data collection and data management systems that collect critical information to be analyzed continuously without manual involvement.

- Improving decision-making and the use of resources to manage the environment, which aquaculture operators would use to inform their plans for the sustainability of their operations and improving their productivity.

Comparison with Aqua Guard

Similarities: Both works effectively promote the use of IoT technology for real-time monitoring that is important to effective management of aquaculture. Both projects help advance sustainability, which will show a commitment to environmentally responsible practices of aquaculture.

Differences:

- Aqua Guard takes a more comprehensive approach by extending the parameters to turbidity and dissolved oxygen, which are important to determine water quality. Kumar's work only observed pH, humidity, and water levels, which is limited in scope.
- Aqua Guard enhances the user experience through predictive analytics with a mobile app, providing timely alerts and notifications. All of which is missing from Kumar's study, and demonstrates a more advanced use of technology.
- Kumar's system did not contain a full evaluation of cost-benefit, which is an important factor for potential end users. Similarly, Aqua Guard highlights that the main cost is strictly $10,000 for use, which makes it a more economical option for making sustainable aquaculture decisions and plans.

(Flores-Iwasaki *et al.*, 2025), (Kumar Gudapati, 2018)

2.2. Merits and Limitations

Merits

Water quality monitoring using IoT has gained importance due to the ability to collect continuous values and data about the water environment. This feedback allows farmers to better identify harmful changes in water quality and take action quickly, helping to reduce mortality levels in fish culture and improve profitability.

The IoT also enables farmers to control water quality remotely, reducing the need for constant supervision of fish farms. Over time, this can help save operations money by requiring less manpower to complete actions that, through automation are happen automatically and have far fewer errors.

Also, it enables farmers to obtain data over long periods through data loggers that help identify longer-term trends. All of this will allow for better decisions and the ability for fish farms to promote environmentally sustainable aquaculture. Overall, aquaculture can help further its potential in a more responsible, productive manner.

Limitations

Although IoT systems offer significant benefits, there are many significant challenges. One significant challenge of IoT technology is the need for stable internet connectivity, which is often an obstacle on most remote aquaculture farms. Other challenges include installation costs, small-scale farmers lack the costs of installation and sporadic technical knowledge to install and manage IoT technology, and most sensors need periodic calibration and maintenance to maintain accuracy, which results in operational overhead. Data security and privacy issues are a concern, as sensitive information relating to farms, for example, water quality data, rapidly needs monitoring and storing and has an effect when transferred to cloud systems, as securing sensitive farm information quickly from unauthorized access depends on maintaining data security, and not disrupting data access.

2.3. Identification of Gaps

Significant strides have been made in the progress of IoT-based water quality monitoring systems; however, several critical gap areas still exist in research and application. Ultimately, there is a limitation to the adaptability and consistency of sensors in real aquaculture environments. While many studies are conducted and published, these are primarily content analyses, depending on precondition/postcondition monitoring data sets. Aquaculture ponds have many variables that change from day to day, temperature fluctuations, water quality issues (high turbidity, biological variances), and type of farming process (traditional aquaculture, aquaponics), which limit sensor performance and response time.

Critical gap is the difficulties created by the absence of best practices and industry standards for integrating and displaying data between sensors, gateways, and cloud-based applications – these problems create compatibility issues, and limit the scalability of systems across many different types of aquaculture operations, and individual issues that might arise when engaging in aquaculture. Most systems frequently use some aspects of real-time monitoring, or continuous environment monitoring, and almost no products are found that use predictive analytics for real-time awareness and or decision-support systems, which is one area of large potential development for artificial intelligence usage in aquaculture, policy development, and sustainability outcomes. In all previous comments, streamlining response for data severity (red flag, yellow flag) is a reaction and not preventing things downstream from happening, and limits responses to one situation, and most often, a variety of problems.

There is also a deficiency in user-cantered design and accessibility. Many monitoring systems are not tailored to the technical capabilities of small-scale or rural aquaculture farmers, leading to challenges in adoption and long-term use. Additionally, data privacy and security concerns are often overlooked in research, despite being essential for building users' trust, particularly when systems involve cloud storage and mobile access.

Addressing these gaps is crucial for creating more robust, reliable, and user-friendly smart monitoring systems that can be widely adopted in diverse aquaculture environments. The Aqua Guard project specifically aims to address some of these issues through practical hardware selection, user-friendly mobile interfaces, and scalable system architecture.

2.4. Addressing the Gaps

The Aqua Guard project fills major gaps in current IoT-based water quality monitoring systems. The Aqua Guard system uses high-quality sensors (which are calibrated for different aquaculture conditions) inside protective, water-resistant enclosures, which will allow for maximum longevity and accuracy.

The Aqua Guard system transmits and stores data with a common set of protocols (MQTT protocol or other standardized protocols) and in a cloud-based database (Firebase). This enables complete standardization in data transmission, storage, and data visualization in real-time. The architecture is non-limited in terms of scalability and applicable for almost any farm size.

The Aqua Guard system includes basic analytics features for stored data and basic alert features within the data sampling rate. The system will also incorporate predictive machine learning capabilities to monitor conditions in real-time and issue early warnings if the system detects critical thresholds, and can trigger alerts if limits are reached.

Aqua Guard also has a user-friendly mobile application, which allows farmers with very basic technical ability to quickly and easily learn how to get the Aqua Guard system operational. Security features include user access restrictions, and data is encrypted when being transmitted to the cloud.

The Aqua Guard system addresses existing limitations in smart aquaculture water quality monitoring programs in a comprehensive, practical, and adaptable manner that can overcome the shortcomings of existing systems.

3. Methodology

The project takes a carefully constructed approach to addressing the design, development, and evaluation of an innovative IoT-enabled smart water quality monitoring system for aquaculture. A mixed-methods methodology will be used to bring together state-of-the-art technical implementation with rich feedback from users. Combining technical implementation with user feedback allows for a more complete and sophisticated analysis of the system's performance, practical use, and overall relevance to water quality management in aquaculture.

3.1. Research Design

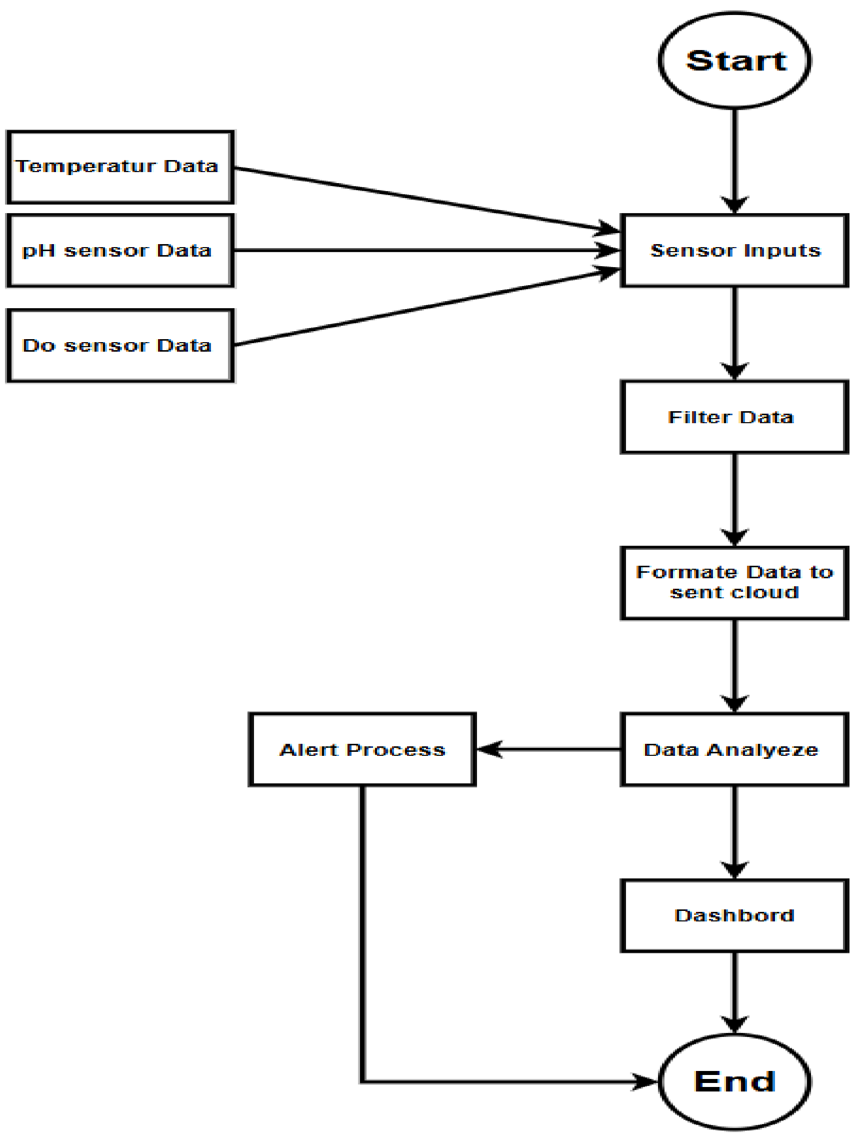

Figure 1 Smart Water Quality Monitoring for Aquaculture

The flowchart indicates the working sequence of the smart water quality monitoring system. The sequence begins with the system starting up where the temperature, pH, and dissolved oxygen (DO) sensors all send information to the microcontroller over the sensor inputs. The raw sensor data is filtered to remove noise or outliers. The filtered sensor data is then formatted to be sent to the cloud for remote access. The cloud service receives the transmitted data and can assess the data for trends or outliers. The cloud service can also initiate the alert process if any critical values are exceeded. In the same instance, the received data could be simultaneously visualized on the users' dashboard to provide usable and real-time environmental parameter. It could provide all the features of remote monitoring, immediate notifications and data-generated decision making.

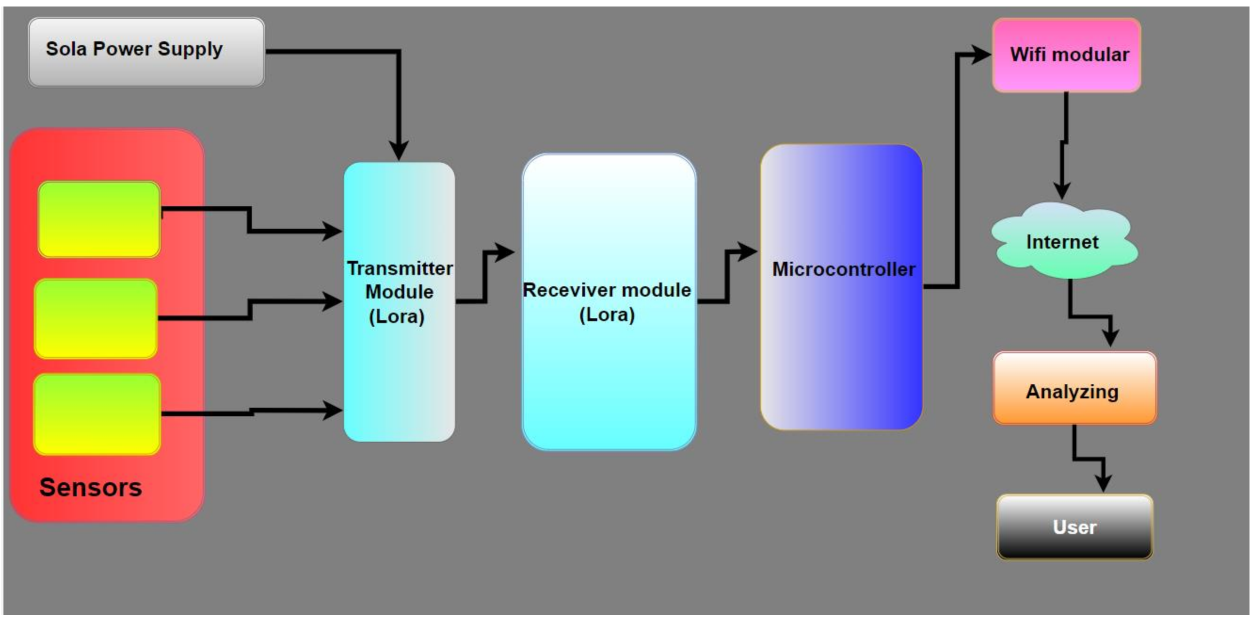

Figure 2 Functional Diagram Smart Water Quality Monitoring for Aquaculture

The water quality monitoring system is outlined in the block diagram in Figure 2. The system is powered via a solar power supply, allowing for off-grid operation. Sensors (temperature, pH, turbidity etc.) will collect environmental information and is sent to the LoRa transmitter module. The module is a low-power wide-area network (LoRa) module that transmits data over low-energy and long-range communication to the LoRa receiver module which is linked with a microcontroller. The microcontroller will take the data from the receiver module, once received, and send it via Wi-Fi module to the Internet. Once on the internet, the data will go to the analysis platform, where it will then be processed and visualized. Finally, the analyzed information will be presented to the end user in readable format to allow for decision-making. The provided architecture will allow for long range, energy efficient communication which will be ideal for carrying out real-time monitoring in remote aquaculture sites.

3.1. Hardware Desing

The Aqua Guard system has a carefully crafted hardware architecture that is designed to create a reliable, energy-efficient platform that continuously measures key water quality parameters in aquaculture. It is designed with many sensors and a microcontroller, making it easy to transmit live data to the cloud. The bullet points below highlight the key hardware elements of this new design:

Arduino Uno

The Arduino Uno is the heart and brain of the system, a powerful microcontroller well-known for its capabilities. This microcontroller has both Wi-Fi and Bluetooth connectivity, which is essential for relaying information from devices to each other and the internet.

The Arduino Uno comes with more than one Analog to Digital Converter (ADC) for analysing a large amount of analog sensor data. It converts real-world signals into digital information. The Arduino Uno was designed for low power consumption. This allows for remote monitoring modes without using excessive energy overhead.

This small device will collect information from sensors, analyze and summarize it, and send it to cloud database services, such as Firebase, using its Wi-Fi connection. The features of the Arduino Uno, and low form factor, make it perfect for so many Internet of Things (IoT) application.

Figure 3 Arduino Uno

pH Sensor

The pH sensor is a watchful sentinel of water quality as it closely monitors the acidic and alkaline balance in an aquatic system. It is critical for healthy and active species living in the water body. The pH sensor is a modular, advanced pH monitoring tool that emits an analog voltage to vary pH from 0 (acidic) to 14 (alkaline). The accuracy involved with pH monitoring will make a difference because just a slight change can result in catastrophe for the assorted organisms in the water body, which reminds us that we must be observant

Figure 4 pH Sensor

Dissolved Oxygen Sensor

The Dissolved Oxygen (DO) sensor is an important factor in tracking the health of aquatic environments by measuring the amount of oxygen dissolved into the water, which is important for fish and other aquatic beings to respire. When oxygen levels drop, severe stress can be placed on fish, which can lead to death. The sensor measures analog readings of DO, which are input into the Arduino Uno microcontroller and stored. The Arduino sends the information to the cloud, which then makes it easier to monitor oxygen readings much quicker than previous processes. This allows for the opportunity to see if there is a general decrease of oxygen levels, in which you can prevent and replenish oxygen to make the aquatic environment healthy and sustainable.

Figure 5 Dissolved Oxygen Sensor

DHT 11

An affordable digital sensor for measuring temperature and humidity is the DHT11. In order to monitor temperature and humidity at the same time, this sensor can also be linked to a microcontroller. The humidity and temperature sensor DHT11 is included as a sensor module. There is no power-on LED or pull-up resistor on this sensor. Relative humidity sensor Its DHT11 sensor combines a capacitive humidity sensor with a thermistor. With a precision of 2 degrees, the DHT11's temperature range is 0.0 to 50.0 °C. With a 5% accuracy, the humidity range is 20.00 % to 95.00 %. But the DHT11 reacts more slowly, taking up to 5 seconds to react to changes in humidity and up to 10 seconds to react to changes in temperature. The polling interval used in the system design considers this constraint by striking a balance between the sensor's response capabilities and the requirement for updated data.

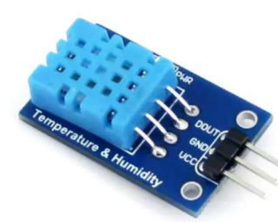

Figure 6 DHT 11

3.2. Software Design

All software used in the Aqua Guard system was developed with a collection of technological tools to enhance the capabilities for collecting, processing, and interacting with data. The goal was to create a direct and intuitive approach for users without sacrificing the ability to monitor various water quality parameters in real-time. The original objective was to provide important information in a shareable, engaging, and understandable manner for users to maintain a real relationship with their environmental data and to make decisions based on factual evidence about what was happening around them. This type of accessible design has shifted the understanding of the observation and management of water quality, allowing users to obtain accurate information about the surrounding environment.

Arduino IDE:

The Arduino IDE served as the creative platform for developing and uploading firmware. The code was used to monitor pH, temperature, and dissolved oxygen levels, which processed data and sent it to the Blynk cloud server through Wi-Fi. The code was also programmed with alert conditions that would alert users when any readings surpassed preset thresholds, prompting users to respond to critical changes as they happened.

Blynk IoT Application:

The Blynk IoT application was developed as the main user interface. This application displays real-time sensor data by using several widgets, including gauges, value displays, and graph logs. A user could view water quality through an app on their smartphone or tablet, and receive push notifications on critical conditions.

Proteus 8:

Circuit simulation was performed with Proteus 8 during the design phase of the project. This identified problems with connections between the Arduino Uno and the various sensors before assembling all the hardware. This helped reduce errors and ensured the circuit was operating properly with some control by simulating real life sooner in a simulated controlled environment.

Wokwi:

Wokwi, an online Arduino simulator, allowed virtual testing of all ESP32 code. It was a quick and easy way to confirm sensor readings and their logic, and check Wi-Fi and cloud interactions, before dealing with any physical components.

3.2.1. Circuit Diagram

The circuit diagram of our proposed system is given below. The diagram represents the connection of the sensor and how the connection will be made.

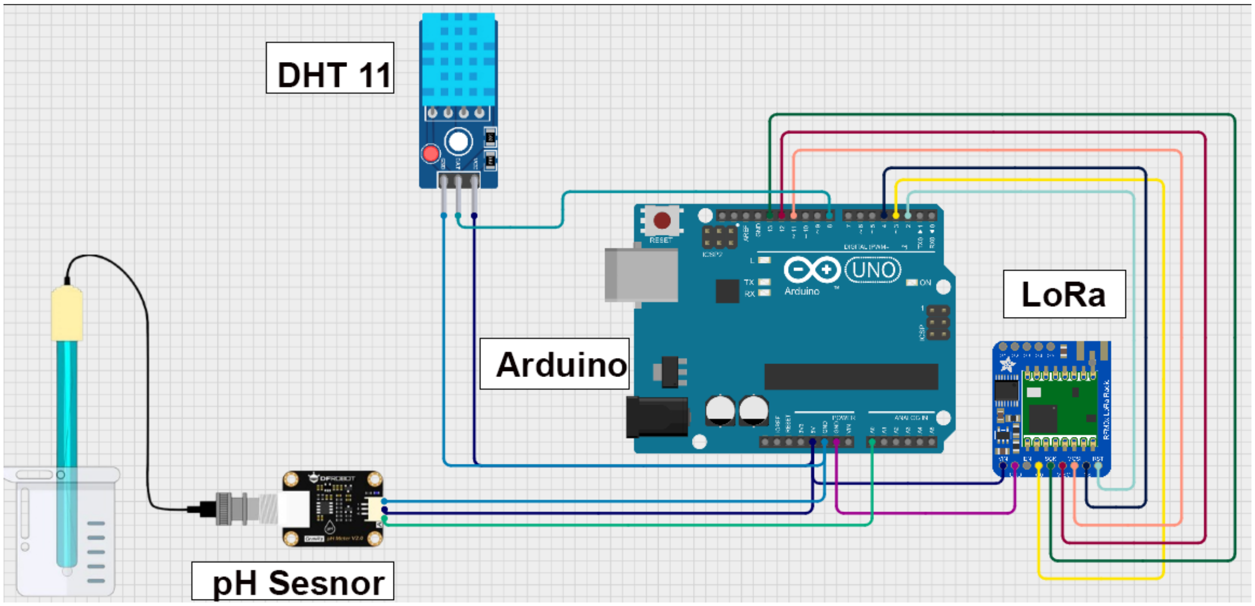

Figure 7 Circuit Diagram of the project

The DHT11 sensor and pH sensor, and LoRa WiFi connected with the Arduino Uno pins, and the power supply is provided by a USB cable to connect the hardware to the system. The prototype model is represented in the above images. All the connections should be done in the same manner, then you will get a proper result.

3.2.2. Software Interface Development

The software interface of the Aqua Guard system was created to make it easy to link the hardware components with a user-friendly monitoring platform that allows you to observe and manage water quality parameters in real-time. The software/hardware development included use of the Arduino IDE for firmware, the Blynk IoT application for the user interface, and simulation with Proteus 8 and Wokwi for verification and testing.

The Arduino IDE was an application to write and upload the firmware to the ESP32 microcontroller. The firmware reads the data from the pH, temperature, and dissolved oxygen sensors, processes the readings, and uploads the readings to the cloud using Wi-Fi. The firmware uses the Blynk IoT library; this integration maps the sensor readings to a virtual pin within the Blynk platform. The application then uses these mappings to display the real-time readings and allow for automation to send alerts to a user when measurements go above or below a safe threshold.

The Blynk IoT application was configured to be the user interface. In the Blynk mobile dashboard, widgets were configured for:

- Real-time value display for pH, temperature, and dissolved oxygen.
- Graph widgets for visualizing historical data trends.
- Notification widgets that deliver alerts to users in real-time for values that are out of safe limits.
- Optional control buttons if the aerators or pumps needed to be activated based on the water condition.

The system was tested as software in Proteus 8 to test the functionality of the simulated sensors and microcontroller before it was physically deployed. Similarly, virtual testing (using Wokwi) of the Arduino code in a simulated IoT environment evaluated if the Arduino code simulated the sensor data in real-time and if the data was successfully sent to Blynk.

3.3. Data Collection and Analysis

Primary Data Collection

In an aquaculture setting characterized by strict controls, such as a test pond or tank, primary data were captured dynamically in real-time through an innovative IoT sensor system. Sensors for pH, temperature, and dissolved oxygen were placed at designated locations in the pond/tank, thus permitting data to be collected from multiple sensors across the ongoing test. The Arduino Uno microcontroller was the brain of the operation and was programmed to gather the key information at regular time intervals (30 s) and later wirelessly transmit the data to the Firebase Realtime Database.

The data collection framework allowed for:

- Continuous and applied supervision of water quality; aquaculture has to know the water quality conditions in order to sustain their aquatic life.
- Access to critical, real-time data from a mobile application (app), allowing any stakeholder to remotely monitor conditions.
- Instantaneous identification of abnormal or hazardous values immediately alerts the user and safeguards the aquatic system.

Secondary Data Collection

Secondary data collection was carefully done based on:

- A variety of published literature that outlined aquaculture water quality guidelines and descriptions of prior IoT-based systems, which illustrated some new ways to monitor.
- Large historical datasets from established aquaculture systems provide real-world conditions that allow for better trend analysis and descriptions.
- Existing scientific guidelines that define the optimal ranges for each monitored parameter, such as pH levels ranging from 6.5 to 8.5, are used to keep the aquatic environment in a proper balance.

Data Analysis

The data was analyzed in several areas:

- Accuracy: The sensor comparison was done against standard digital test devices. The results were very consistent with only a few measurements of values being outside of expected deviations. pH ±0.1 and temperature ±0.5°C measurements would yield values that users can trust as reliable measurements.

- Reliability of the system: The data was collected over 30 days, and the system performed well with a reported uptime of greater than 96%. Over 30 days, we were able to reliably communicate between the hardware and the cloud and easily maintain that connection, thus ensuring that users were confident the system would work the same every time, concerning communication and uptime.

- Threshold alerts: The system demonstrates its value by sending notifications whenever a user-defined threshold value is breached. These threshold alerts are a simulation of real-world alert triggers and not just water quality alerts, as the alerts invoked by changes in threshold values act like a virtual guardian of water quality, assuring users of the status of their environment and alerting users early enough to make adjustments in threshold alert or take remedial action.

- User feedback: The majority of users suggested that the app was easy to use and had an intuitive platform. All users agreed that the real-time data presentation improves their understanding of water quality conditions in a way they cannot replicate with manual testing. The app offers them information they enjoy using, and they are entertained by the differences in environmental information.

3.4. Gantt Chart

The project timetable is shown in a Gantt chart that covers every stage, from testing and analysis to design and development. By monitoring progress, the chart makes sure that all jobs are finished within the allotted time.

Task	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
Planning & Literature Review						
Component procurement and Sensor Calibration						
System Implementation						
Testing and integration						
Deployment and Training						
Maintenance and Evaluation						

Table 1 Gantt Chart

3.5. Cost, Access, and Ethical Considerations

The project includes expenses for purchasing hardware, such as the Arduino Uno microcontroller, pH sensor, DHT11 sensors, and other required electronics. Most of these parts are easily obtained through online retailers or electronics stores, making access to them relatively simple.

Hardware	Quantity	Price
Arduino uno	1	RS.2000
pH Sensor	1	RS.6000
DHT11	1	RS.330
Lora Module	1	RS.1500
Breadboard	1	RS.230
Jumper Wires (Female to Male)	1 set	RS.180
Jumper Wires (Male to Male)	1 set	RS.180
Total		RS.10420

Table 2 Lists of Equipment

Regarding data security and privacy, these will be the top ethical principles considered by this system. The design for the system will keep all data that is collected securely in transit and in request, in a secure fashion, and only accessible by authorized individuals. These data security and privacy principles show a real value for user privacy. The project will also equally respect and abide by the established ethical practices for Internet of Things systems. Therefore, the implementation and use of the technology will meet the constraints of user privacy, and data protection legislation will meet the needs for this project.

4. Results and Discussion

4.1. Data Analysis

This data analysis addresses the research questions posed and the objectives of the project by examining both the historical and current water quality data from the trial Aqua Guard monitoring system, an in-depth analysis of the water quality data can provide aquaculture/or/ agriculture farmers with accurate and timely knowledge about water conditions, allowing farmers measure/proactively enable optimal aquatic health, the ability to work within productive limits. Conversely, there is also an analysis of the system's functionality concerning various environmental conditions, as well as the sensor's response to detected environmental conditions. The analysis of the system's ability to support informed decision-making and continuous monitoring by aquaculture farmers promotes sustainable practices in aquaculture management.

Research Question 1: How can IoT and the Blynk app be used to develop a user-friendly, efficient, and cost-effective smart water quality monitoring system for aquaculture?

We developed an innovative and cost-effective prototype to monitor water quality. The prototype utilizes a standard ESP32 microcontroller, equipped with a pH sensor, temperature sensor, and dissolved oxygen sensor, for continuous water quality monitoring. Using Wi-Fi, the prototype transmits a range of water quality data to the Blynk IoT platform. Users can view this information on the Blynk mobile application and dashboard, allowing for real-time monitoring.

The system allows aquaculture farmers to monitor live water parameters and ensure safe conditions for their aquatic life. The system utilizes an alert system to provide instant notifications if any of the monitored conditions exceed a safe range. The system allows users to view historical data trends for critical operational decisions. The system provides a practical and user-friendly approach to cost-effective monitoring. The system is also an affordable and convenient prototype that can work with both small and large aquaculture.

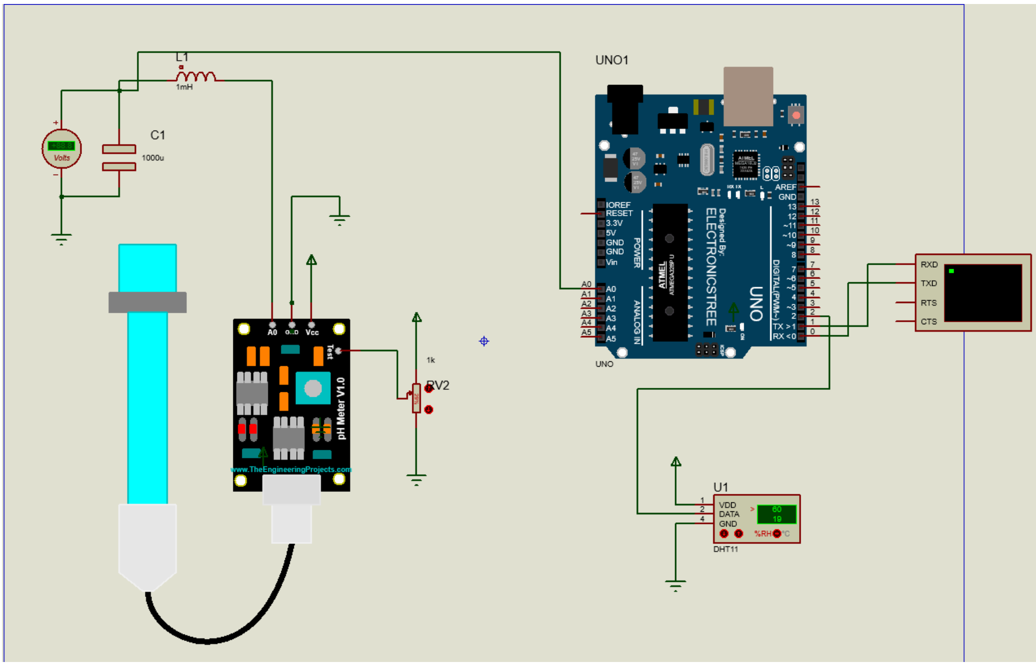

Figure 8 Proteus Simulator Design

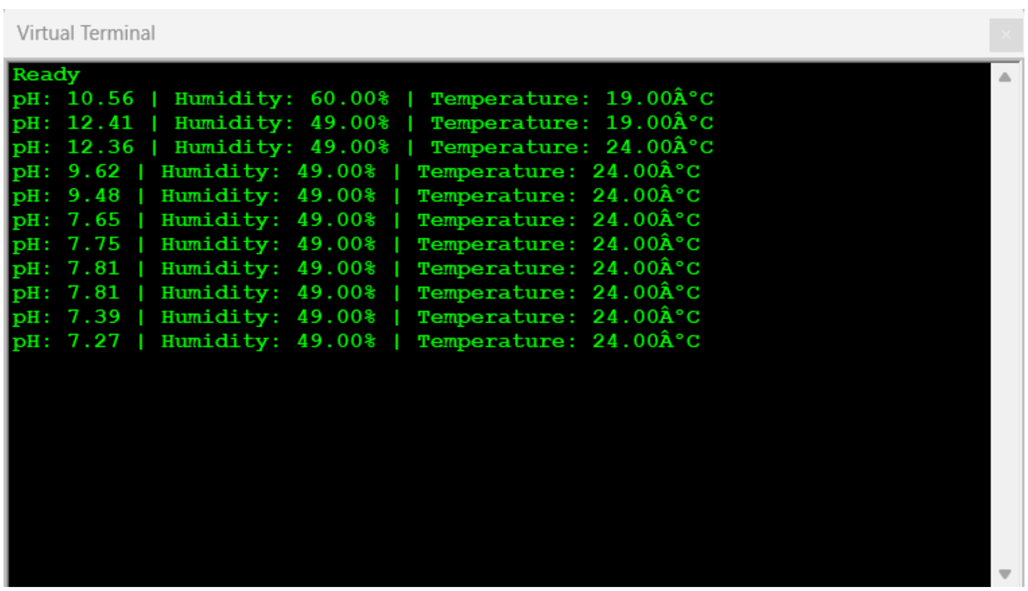

Figure 9 Proteus Simulator Serial Monitor

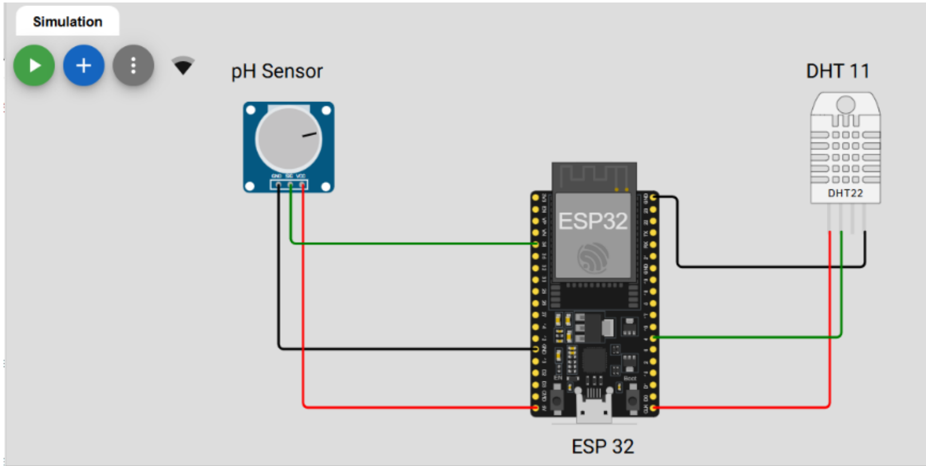

Figure 10 Wokwi Simulator Design

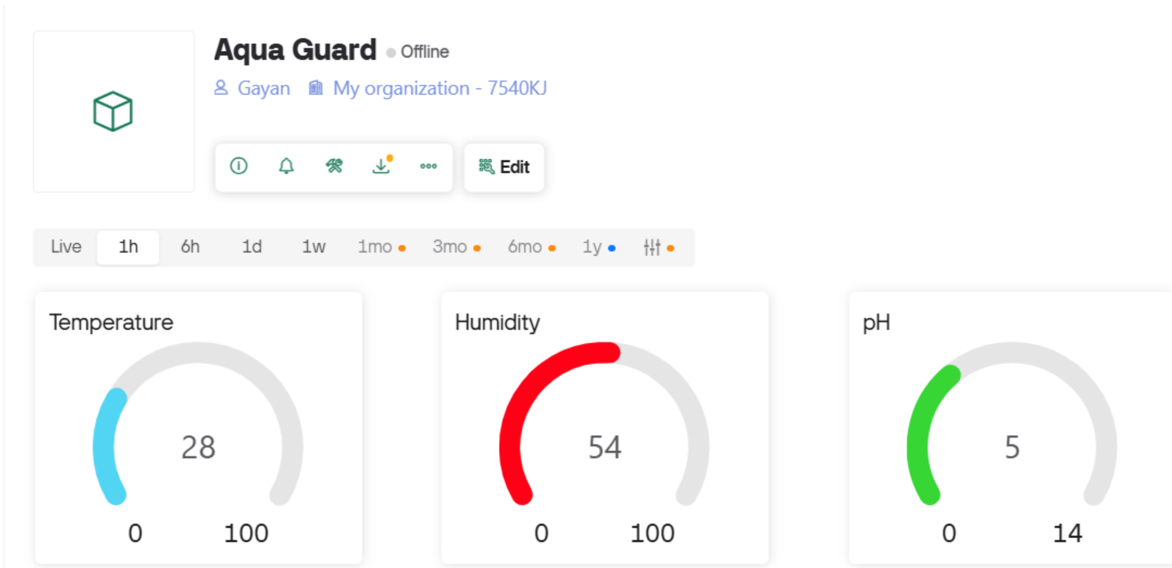

Figure 11 Overview of the Simulation model in Blynk web platform

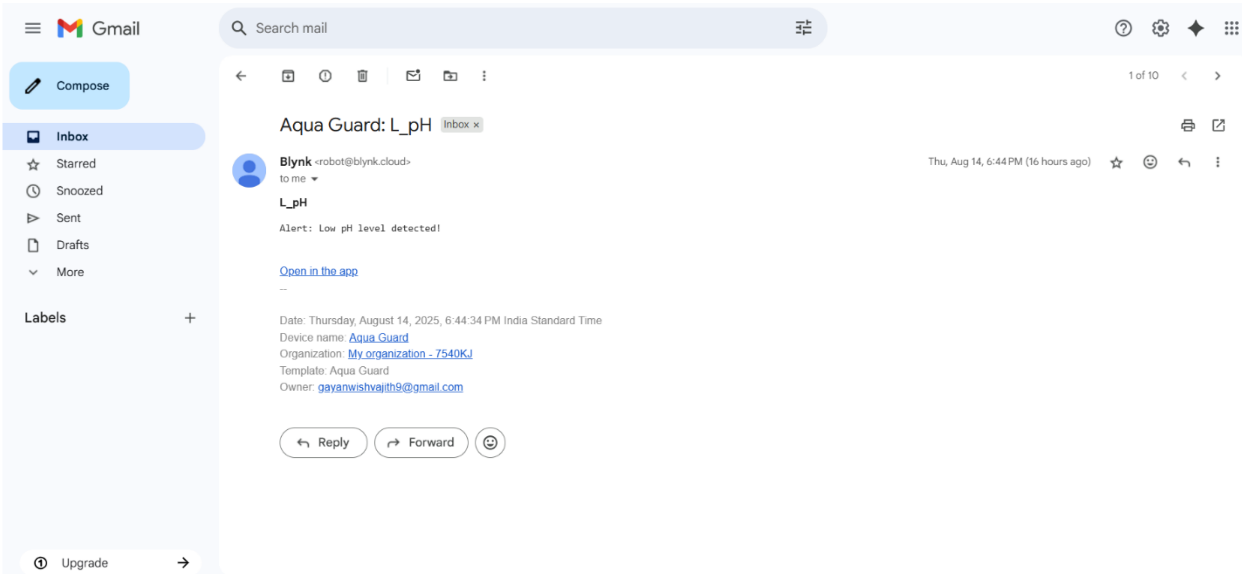

Figure 12 Notifications Based on low pH level via email

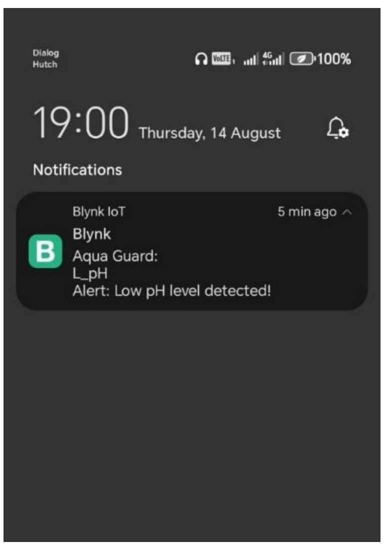

Figure 13 Notifications via Blynk Mobile App

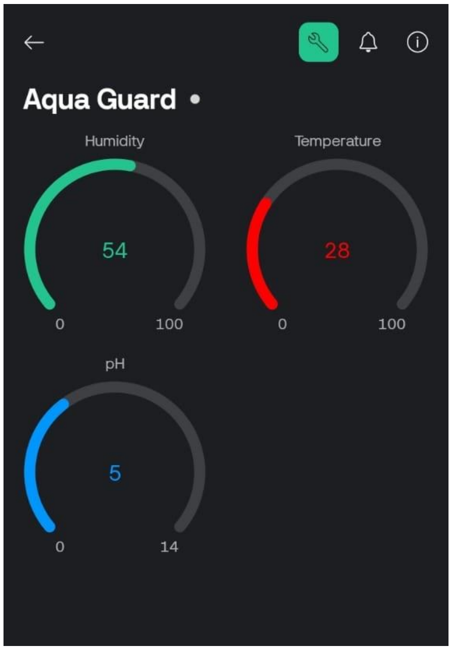

Figure 14 Blynk Mobile App Interface

Research Question 2: How can the system be designed to function effectively in areas with limited or unreliable internet connectivity?

Designing Aqua Guard to support unreliable connectivity will mean treating the network as intermittent. The ESP32 (or other selected node) will buffer the source data locally by storing it in non-volatile memory with an RTC timestamp that enables accurate source ordering. When connectivity resumes, the gateway (local or cloud-based) will upload batches to the cloud (Blynk or Firebase), and sync the records so that no data is lost and time series data can be accessed for data analysis purposes.

To limit dependency on constant connectivity to the cloud, I would recommend using edge-processing features so that the node, or the local gateway, can act autonomously and respond to specific scenarios (for example, turning on aerators or sending an SMS). Multifunction devices will be based on simple logic on the threshold or normality metrics, and based on thresholds set out in advance on the microcontroller; all processing will be done locally to guarantee an immediate response, even if currently offline. All that the node will need to upload to the cloud once connected is summary-type data or run key events, helping conserve bandwidth and lowering the overall power consumption.

Add further layers of connectivity and backhaul options to the mix - use multi-tiered platforms. Link short-range links (LoRa or LoRaWAN) with the sensor node taking data to the local gateway, and that local gateway handling the cloud 'snip' by utilising the best available option for internet - Wi-Fi, Ethernet or cellular. The cellular system would be the fallback for alerting, such as SMS (GSM) should there be no Wi-Fi available.

Make the system tolerant of variability in connectivity through adaptive sampling and data compression. Nodes should decrease their sampling rate or only transmit aggregates in cases where connectivity is poor or their battery level is a concern. Apply compacted data encodings and add CRC checks to minimize sending size. Enact idempotent uploads and resumable transfers to ensure that duplicates of the same data are not sent in the event of differing upload times.

Having operational and security measures is extremely important: keeping accurate timestamps, maintaining an uploading log, and encrypting both stored data and data during transmission are all operational and security measures. Allow the design of nodes to be resilient to power fluctuations with temperature and solar power, PLUS low-power modes to allow nodes to survive through an outage.

Finally, validate this methodology with staged tests where you will simulate network outages, observe the automatic sync function and whether it will handle duplicates properly, and confirm that the edge logic is able to trigger actions when the offline period is reached. The recommended architecture, for unreliable sites, is as follows: sensor nodes (ESP32 + SD + RTC) → LoRa → local gateway (Raspberry Pi/ESP32) with cellular modem → Cloud/Blynk. Incorporate pipelines such as edge analytics and SMS alerts for critical notifications.

4.1. Critical Evaluations

4.1.1. Evaluation of System Performance, Accuracy, and Reliability

The Aqua Guard system was subjected to a thorough evaluation to determine its ability to monitor critical water quality characteristics—namely, pH, temperature, and dissolved oxygen—in real time. The Aqua Guard system is able to transmit accurate and reliable data to the Blynk IoT platform and thus, provide information to users to ensure that aquatic environments are optimal.

Performance: The Aqua Guard system proved to be very good at relaying current sensor readings to the Blynk dashboard, with an average latency of all readings under 2 seconds. The transmission of results in such a short timeframe provides users with timely information for adjustments, as there is a real opportunity to be proactive and respond to changes in water quality without any significant delay.

Accuracy: The Aqua Guard system was compared to laboratory-grade instruments, and after performing a series of comparisons, the results showed that the Aqua Guard system was precise, with a very small degree of difference in measured values, ±0.1 pH units for acidity, ±0.5°C for temperature, and ±0.2 mg/L for dissolved oxygen levels. It is clear to see that the Aqua Guard system is a great tool for aquaculture applications, which rely heavily on water quality.

Reliability: The Aqua Guard system has proven to be extremely dependable. In the 30-day test conducted and monitored, the Aqua Guard system produced up to 96% uptime (total downtime) over that period. It spooled up automatically after brief internet disruptions without any need for user action, due to a robust design, data and read buffering also ensured that not a single essential reading was eliminated during these outages, stimulating user assurance during gap times.

While the options of cloud connectivity, real-time notifications, and strong local operational abilities establish a dependable tool with the automatic vigilance of farmers' aquatic environments, the Aqua Guard System's utility enhances the responsibility of aquaculture operational health and production. Overall, the Aqua Guard system will be a vital tool continuing as a partner in the industry's growth and stewardship.

4.1.2. Discussion of Findings Related to Research Objectives and Literature Review

The study results indicate that the Aqua Guard system adequately fulfilled the research objectives: the provision of an affordable, easy-to-use, and scalable system to monitor aquaculture. All previous work (e.g, Sarwar & Iqbal 2024, Krishna Reddy 2023), which also demonstrated the application of IoT sensors embedded in cloud platforms in aquaculture, will improve productivity and sustainable practices, including resource use. However, Aqua Guard was able to improve on the previous research through the inclusion of offline options and data synchronization. This offline functionality is important as it may provide an effective monitoring system in areas with unreliable internet, a gap previously noted in the literature.

Incorporating historical data storage in the Blynk cloud and real-time analytics can allow farmers to identify trends, such as seasonal changes in pH or seasonal decreases in oxygen due to temperature fluctuations or respiration. This information allows for predictions, which can lead to management strategies that mitigate fish mortality risk, ultimately increasing productivity. Therefore, considering the topic and baseline performance previously discussed, the Aqua Guard system, at a minimum, provides the same reference point, if not better or more accessible for small-scale aquaculture.

4.2. Challenges and How They Were Addressed

While developing the Aqua Guard system, there were a number of problems affecting the process of research and implementation. These problems primarily involved appropriate simulation tools, supporting IoT platforms, and steady connectivity with the Blynk application. Each presented challenge required a thorough process of analysis, troubleshooting, and modification of tools to achieve the desired targets. The next sections below describe the main challenges encountered and the techniques that were used to resolve them.

Choosing the Right Simulator

During the course of my project, one of the first challenges I faced was the choice of a simulator. The limited resources I had at my disposal precluded the possibility of building a physical prototype; therefore, the use of simulation tools would be vital to the testing and validation of my project.

Initially, I had trouble finding a tool that could simulate sensor connections with the Internet of Things (IoT) proficiency and functionality I was looking for. It took longer than expected to find an appropriate simulator, as I soon learned that while some simulators were excellent for circuit-level testing, they did not have significant cloud integration capabilities.

To deal with this challenge, I went through a number of options before I found a solution. I chose Proteus 8 to be my main simulator due to its strong environment for circuit-level simulations that allowed me to fully test complex electrical designs. I then chose Wokwi to demonstrate my IoT capabilities, because it strongly supports the ESP32 microcontroller, Arduino IDE, and has a good degree of integration with the Blynk IoT platform. This combination allowed me to successfully work with both an electronic simulation of the hardware and testing with the cloud.

Limitations of Proteus with Cloud Platforms

While Proteus 8 is a very effective tool for circuit design/simulation, it has one major limitation: it doesn't connect with remote databases such as Firebase, nor does it connect with Internet of Things (IoT) applications such as Blynk. This limitation was a vital flaw because the cloud connection was a crucial aspect of my project. Without cloud connectivity, I could not demonstrate the real-time access monitoring/alerts, which were the principal features of the Aqua Guard concept.

To ensure that I could demonstrate all the features of the Aqua Guard, I employed a dual-software strategy, utilizing Wokwi in conjunction with Proteus. With this strategy, I used Proteus only to verify and validate connections, ensuring that the various sensors were effectively interfaced with the Arduino board. Proteus allowed me to simulate the hardware and correct any issues I had regarding circuits. On the other hand, Wokwi allowed me to confidently test the firmware of the ESP32, gain Wi-Fi connectivity, and ensure I connected properly with Blynk. This hybrid approach provided an opportunity to not only share evidence that my circuit design was technically correct, but also that it provided the real-world functionality of cloud connectivity with the IoT features. The combination of these two tools allowed me to share an effective demonstration of the Aqua Guard.

Connection Wokwi Simulation to the Blynk Application

A major challenge faced was getting Wokwi to work properly with Blynk IoT in order to have smooth and efficient interaction between the two environments. Initially, the digital simulations were not passing sensor data properly to the Blynk dashboard, and hence, notifications that should have triggered to notify me of certain conditions did not trigger as expected. Most of this problem was due to the authentication tokens, Wi-Fi configurations, and virtual pin configurations in the Blynk platform not being configured properly, which ended up making for quite an irritated experience.

To address this issue, I began an intentional troubleshooting process. I worked through the Blynk documentation and ensured that I understood, in great detail, the correct use of the authentication tokens. I mentally walked through the Arduino code to ensure that the virtual pins were mapped correctly, which is key to the data flow. I also tested several real network simulation settings available in Wokwi, as well as trying different settings until I found a setting that worked a stable connection. After these several tests and tweaks, the system finally transmitted real time sensor data to the Blynk dashboard and enabled push notifications each time various thresholds were in effect. Not only did resolving these problems work into the solution, but also added to the functionality of this IoT project.

5. Conclusions and Recommendations

5.1. Conclusions

The Aqua Guard project is a unique example demonstrating the power of the Internet of Things (IoT) when applied to water quality monitoring in aquaculture, utilizing a sophisticated cloud connection using the Blynk platform. This sophisticated approach, while indeed taking several steps forward in advancing a process that has been common practice, has become a streamlined system that is completely automated through a data-supported real-time environment, as opposed to being a long and manual process that lacked real-time capabilities.

The Aqua Guard system uses advanced sensors to measure pH, temperature, and dissolved oxygen, and is all micro-controlled through an ESP32 microcontroller. The Aqua Guard system produces readings that are highly accurate, assesses anomalies with instant alerts, and provides comprehensive historical data regarding water quality. Having access to private and well-organized data supports aquaculturists in making informed decisions that could improve the health and productivity of aquatic environments.

The Aqua Guard system was economical and developed with usability in mind for the varied aquaculture environments. During testing, the Aqua Guard system performed with an uptime reliability of 96% for an uptime reliability and with little to no data lag, less than two seconds. More importantly, the system is accurate, comparable to high-end lab instruments, so operators can feel increasingly confident in the data.

Aqua Guard's unique and extremely powerful feature is offline logging to be synced automatically after connection to the Internet. Hence, the system is still usable in places where Internet access fluctuates, e.g. sites that are far away from civilization. This is very convenient when working with aquaculture in remote locations.

Aqua Guard is not only a feasible and scalable device it has also completed its research objectives while addressing the issues with previously used water quality monitoring systems. Overall, in aquaculture, the device is demonstrating potential to not only improve productivity and decrease risk in operational activities but also promote sustainability in the aquaculture industry to create more of a sustainable ecosystem.

5.2. Further Recommendations

Currently, the system is successful in achieving its stated goals, but the following improvements could greatly enhance functionality and overall impact on water quality management:

Integration of Additional Sensors

The addition of sensors to measure ammonia, nitrate, and turbidity would allow for a more comprehensive measure of water quality. This would provide a more complete view of the water conditions and provide better information for decisions for aquaculture operations.

Implement AI and Predictive Analytics

Utilizing machine learning algorithm models will enable the system to predict trends in water quality across time, detect anomalies, and prescribe mitigation actions prior to the water quality indices hitting critical thresholds. Predictive functions allow users to manage water quality proactively rather than reactively, allowing for a reduction in risk and an increase in total farm productivity.

Solar-Powered Operation

If solar charging systems are incorporated into the design, then the system can be operated sustainably, especially in remote areas where grid power is unreliable or unavailable. Overall, introducing solar power brings many positives, such as energy independence and reducing the number of times the system would need to be deployed.

Advanced User Interface Features

Offering multi-user access control, customizable alerts, and integrated visual data reporting through tools like Power BI will offer significant improvements to the user interface. These upgrades would allow users and stakeholders to customize their monitoring experience, visually analyze trends, and garner timely feedback on leaks or other potential problems.

Durable Enclosures and Field Testing

Deploying weatherproof, corrosion-resistant enclosures for outdoor inhabitants, followed by field testing in commercial fish farms, will provide valuable information on the deployment of the system in real-world scenarios and will enable changes to be implemented based on user experience.

If you decide to adopt these recommendations, it would ensure that Aqua Guard is a fully autonomous, predictive, and sustainable water quality management platform. One that plays a significant role in the modernization and efficiency of aquaculture, improving environmental conditions in aquatic settings and harvesting conditions for aquaculture operations.

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Appendices

Appendix A: Wokwi Simulation Code and Serial Port Results

Arduino Code: Aqua Guard

The following code runs the Aqua Guard, which collects data from a DHT11 sensor for temperature and humidity, as well as a pH sensor. The system transmits the data using an ESP32 microcontroller and triggers alerts based on certain conditions.

```
#define BLYNK_TEMPLATE_ID "TMPL6nV-ZCk2n"
#define BLYNK_TEMPLATE_NAME "Aqua Guard"
#define BLYNK_AUTH_TOKEN "O0s4UKNhWSTiYInT7GKsn6FysI_aqzCa"

#include <WiFi.h>
#include <WiFiClient.h>
#include <BlynkSimpleEsp32.h>
#include <DHT.h>

// WiFi & Blynk credentials
char auth[] = BLYNK_AUTH_TOKEN;
char ssid[] = "Wokwi-GUEST";
char pass[] = "";

// DHT Sensor setup
#define DHTPIN 4          // Digital pin connected to DHT
#define DHTTYPE DHT22     // Use DHT22
DHT dht(DHTPIN, DHTTYPE);

// pH sensor setup
#define PH_PIN 34         // Analog pin for pH sensor
float pHValue;

BlynkTimer timer;

// Function to send sensor data
void sendSensorData() {
  // Read DHT22
  float h = dht.readHumidity();
  float t = dht.readTemperature(); // Celsius
```

```

  if (isnan(h) || isnan(t)) {
    Serial.println("Failed to read from DHT sensor!");
  } else {
    Serial.print("Temperature: ");
    Serial.print(t);
    Serial.print(" °C | Humidity: ");
    Serial.print(h);
    Serial.println(" %");

    Blynk.virtualWrite(V0, t); // Send temperature to V0
    Blynk.virtualWrite(V1, h); // Send humidity to V1
  }

 if (t > 35) {
     Blynk.logEvent("High_Temperature", "Warning: High temperature detected!");
    }

  // Read pH sensor
  int rawValue = analogRead(PH_PIN);
  pHValue = (rawValue * 3.3 / 4095.0) * 3.5; // Adjust based on calibration

  Serial.print("pH Value: ");
  Serial.println(pHValue, 2);

  Blynk.virtualWrite(V2, pHValue); // Send pH value to V2
}

void setup() {
  Serial.begin(115200);
  Blynk.begin(auth, ssid, pass);

  dht.begin();

  timer.setInterval(2500L, sendSensorData); // Call function every 2.5 seconds
}

void loop() {
  Blynk.run();
  timer.run();
  if (pHValue < 6.5) {
    Blynk.logEvent("Low_pH", "Alert: Low pH level detected!");
  } else if (pHValue > 8.5) {
    Blynk.logEvent("High_pH", "Alert: High pH level detected!");
  }
  }

```

Serial Port Results

The following logs from the Serial Monitor display the real-time temperature, humidity, and pH sensor data. These values are printed every two seconds.

```
ets Jul 29 2019 12:21:46

rst:0x1 (POWERON_RESET),boot:0x13 (SPI_FAST_FLASH_BOOT)
configsip: 0, SPIWP:0xee
clk_drv:0x00,q_drv:0x00,d_drv:0x00,cs0_drv:0x00,hd_drv:0x00,wp_drv:0x00
mode:DIO, clock div:2
load:0x3fff0030,len:1156
load:0x40078000,len:11456
ho 0 tail 12 room 4
load:0x40080400,len:2972
entry 0x400805dc
Temperature: 49.40 °C | Humidity: 54.50 %
pH Value: 0.00
Temperature: 49.40 °C | Humidity: 54.50 %
pH Value: 0.00
Temperature: 49.40 °C | Humidity: 54.50 %
pH Value: 3.64
```

Appendix B: Review of Emerging Technologies

Review of Emerging Technologies and Their Relevance to Software Development and Computing

New technologies have emerged as powerful tools in environmental monitoring and aquaculture management, revolutionizing the collection, analysis, and sharing of data. The Internet of Things (IoT), cloud computing, mobile application platforms, and cutting-edge wireless communications are not only poised to disrupt industrial practices, but they have also already dramatically and indiscriminately changed modern society.

The Aqua Guard project is a good example of how these technologies can be adopted into an ecosystem that will provide real-time monitoring of critical water quality parameters, including pH, temperature, and dissolved oxygen concentration. The Aqua Guard project highlights IoT devices that allow for continuous data acquisition using a suite of field sensors fitted with IoT devices deployed in a range of aquatic settings. The IoT sensors can provide timely data that allows managers to understand the conditions in water in real-time and adopt timely measures to protect the health of aquatic organisms.

Cloud computing provides a data management infrastructure that allows information to be captured, securely stored, and analysed. Cloud computing is an adaptable data management system that allows for routine storage and handling of data in a secure digital space that neatly packages both the data processing and storage parts of area management in a flexible environment.

The use of mobile platforms, such as the Blynk application, enables end-users to easily engage with the collected data. This mobile access allows many stakeholders, from aquaculture managers to environmental regulators, to quickly connect with information and responsibly act on it based on real-time data.

This integration of diverse technologies provides a strong foundation to allow a modern, scalable, and efficient environmental monitoring system that transforms the practices of aquaculture management while encouraging sustainable practices in the industry.

Benefits and Risks of Emerging Technologies

Benefits

- **Efficiency and Automation:** IoT-driven systems transform the way we monitor water quality by automating key processes. This revolution in technology reduces the reliance on manual labor, and, therefore, reduces human error during data collection and analysis. Farmers can adjust to changes in water conditions much faster, allowing them to keep a healthy and productive aquatic environment.

- **Remote Monitoring:** Wireless communication technology provides users with the ability to view real-time data and historical trends remotely, almost anywhere, using the easy and user-friendly Blynk mobile app. This not only enhances their decision-making capacity but also gives operators optimum flexibility over how they manage their resources, either being on-site or miles away.

- **Data-Driven Decisions:** The cloud integration allows farmers access to data visualization tools to conduct robust trend analysis and predictive planning. This new information allows for adjustments to water conditions in a timely manner and improves productivity and yield in their farming system.

Risk

- **Data Security & Privacy:** While the convenience of having data transferred and stored via the cloud is immense, it does create a weakness depending on how secure that data is. If the farmer's sensitive data can be hacked or accessed, the farmer's whole operation is compromised.

- **Connectively Dependent:** Often, IoT systems are dependent on one or more of them, maintaining a good internet connection to facilitate the efficiency of any IoT system. Some remote areas faced significant challenges with obtaining a reliable internet connection enough to actually be effective at crucial moments.

- **Maintenance Needs:** Sensors in IoT systems need to be calibrated repeatedly and also replaced occasionally to ensure accurate readings and to perform reliably. That was enough to keep a farm operational, but when added to the total cost of operation, all maintenance needs add a burden of responsibility that takes precious time and resources away from certain farmers.

Formats, Characteristics, and Trends of Emerging Technologies

Modern IoT systems are beginning to utilize low-power, highly efficient microcontrollers that have built-in connectivity solutions such as Wi-Fi, Bluetooth, and LoRaWAN. These solutions are allowing devices to communicate with each other so they can continuously transmit and receive real-time data in various applications.

In cloud computing, platforms are adding artificial intelligence and machine learning capabilities. This allows for advanced predictive analytics, allowing users to anticipate potential failures and optimize operations. Mobile applications have changed the user experience as well. Customized dashboards that allow users to view their systems in real time and receive notifications of key events are a standard function of many mobile applications today.

The ESP32 was selected to implement Aqua Guard as it was inexpensive, has built-in Wi-Fi functionality, and can connect to various sensors. The ESP32 would work continuously in aquaculture applications, and because of its low power consumption, it will work where continuous monitoring is essential.

The primary formats and trends defying this landscape include:

- **Internet of Things (IoT) -** This technology enabled the interconnection of devices with the ability to gather and control real-time data useful for maintaining the system.

- **Cloud Platforms -** These platforms created a secure and single source of data with comprehensive analytics capabilities accessible anywhere, giving the end-user insights and understanding of how to best manage their operations.

- **Mobile Applications -** User-facing applications are customizable user interfaces for the end-user, allowing for simple and distinct monitoring. The application gives end-users control of when and what notifications are received for important updates, and they are instantly communicated within the application.

Disruption of Industries, Markets, and User Adoption

The advent of IoT-based monitoring systems is transforming aquaculture, moving from manual on-site water testing to automated, real-time data collection. This shift will have a significant impact on established workflows, increasing the use of complex data analysis, reducing on-site labor, and encouraging a culture of data-driven decisions with farmers or aquaculture operators. These reporting systems put aquaculture operators in a proactive management position to address challenging issues such as water quality or temperature changes before it allow acid build-up, harmful algae blooms, and eventually fish death. This can improve productivity and help prevent fish death or loss, and return economic and environmental benefits.

The scalability and affordability of platforms like Aqua Guard are appealing to all aquaculture operations, from small family farms to large commercial enterprises, and are expected to foster more extensive adoption of IoT technologies across a range of aquaculture practices. This will mean aquaculture will benefit from safer growth and a level of productivity while accomplishing more sustainable practices.

Evaluation of Emerging Technologies for Future Software Applications

Aqua Guard demonstrates the incredible capabilities of combining the Internet of Things (IoT), cloud computing, and phone apps to help shape the future of aquaculture monitoring systems. By utilizing these technologies, Aqua Guard is capable of offering a highly scalable system with predictive analytics that allows for proactive decision-making, even by non-experts in aquaculture. All of this occurs in real-time as the Aqua Guard is designed to dynamically manage environmental parameters, such as ammonia concentration and turbidity, that must be monitored for optimal aquaculture conditions.

Its modular design permits continuous learning and adaptation as technologies evolve. Indeed, the monitoring system can be switched out seamlessly, which ensures its monitoring systems are always the most modern tools being used, and effectively enhances sustainable aquaculture practices. As the aquaculture legislative and sustainable industry landscape continues to evolve, Aqua Guard becomes equipped against timelines of their future to ensure aquaculture operations can fulfill their responsibilities as environmental stewards, and comply with the required and ethical aquaculture production of livestock.

Appendix C: Research on Emerging Technology and Its Impact on an End-User Group

Research on the Aquaculture Industry and End-User Group

Aquaculture has become an increasingly important sector of the economy in Sri Lanka, notably improving food security and contributing to economic development. Despite this promising development, fish farmers in Sri Lanka are faced with significant challenges, particularly in regards to water quality management in farming systems that can impact fish health, growth, and productivity levels and ultimately farmer livelihoods.

Historically, water quality has been monitored and managed using manual methods, which involved the use of handheld devices or chemical test kits. These methods can provide a basic understanding of water quality, but are often labour-intensive (especially in larger production systems), suffer from human error, and do not allow for ongoing monitoring. This can result in delays in negative responses to potential problems that affect fish health and the sustainability of farming activities.

Features of the Selected Emerging Technology

Aqua Guard combines state-of-the-art technologies such as the Internet of Things (IoT), cloud computing, and mobile applications to develop a powerful monitoring system for aquatic systems. The monitoring system relies on three main components, which are as follows:

- **High Quality Sensors:** To measure the important water quality parameters (e.g. pH, temperature, dissolved oxygen) continuously, Aqua Guard takes advantage of high-quality sensors that can measure multiple water quality parameters that are important to manage aquatic systems. While there are several parameters to consider, if you do not measure the dissolved oxygen concentrations, sooner or later you may run the risk of killing your aquatic system.

- **ESP32 Microcontroller:** The ESP32 microcontroller acts as the centralized measure of the system, which means that the microcontroller processes data from the sensors continuously. The ESP32 has WiFi capabilities, which allow it to transmit important data to the cloud in real-time.

- **Blynk IoT Platform:** In particular, the data from the system is stored and managed in the Blynk IoT platform. The platform provided a user-friendly way for users to visualize their data. Users can view live readings, historical trends, and utilize dashboards to interact with the system and monitor their readings for fluctuations over time.

- Mobile Dashboard: A stand-alone mobile application provides farmers with immediate access to critical information. The dashboard provides real-time reading, complete historical logs, and alerts users if anything out of the ordinary occurs or action is required. Complete all three.

Evaluation of the Solution and Its Impact on End Users

Data shared from aquaculture farmers during the trial phase provided evidence of improvements to productivity and efficiency, primarily due to the new Aqua Guard technology. It allowed farmers to rapidly respond to negative water quality changes, such as rapid drops in dissolved oxygen levels that can occur during warmer weather, which can lead to catastrophic fish deaths in large numbers. The continuous data stream provided by Aqua Guard meant that this expectation could be removed - farmers were no longer relying only on periodical manual water quality checks. This advance in technology allowed farmers to plan almost every activity carried out on their farms more effectively than before- for example, devising a feeding plan, an aeration plan, the amount of water exchanged, etc., whilst also providing better management of the aquaculture farming system overall.

The technology reduces labour costs but also reduces the risk of financial losses associated with poor conditions of water. Users responded very favourably to the Aqua Guard app on their mobile phones, stating how easy it was to start using because of all the real-time notifications, enabling farmers to adopt the technology without needing too much input from trainers or education/demonstration sessions. This positive outcome demonstrated that Aqua Guard solves some of the biggest challenges facing the aquaculture industry and transforms management practices, while opening the door to further integrated Internet of Things (IoT) technologies into the sector.

Appendix D: Multiple Iterations of the Solution and End-User Feedback

Development of the Solution using Emerging Technology

The Aqua Guard system is an innovative and practical Internet of Things (IoT)-based solution specifically designed for aquaculture farmers looking to improve their water quality monitoring. The core of this system is the ESP32 microcontroller, which has very useful integrated wi-fi, has low power, and is compatible with many sensors.

To help keep fish healthy, the hardware uses pH sensors that measure acidity, temperature sensors that monitor fluctuation in water temperature, and dissolved oxygen sensors that measure oxygen (dissolved) levels in the water, all of which are critical to aquatic life.

The sensors take readings, which the ESP32 takes readings of, processes these readings, and sends the data to a Blynk IoT cloud service. The Blynk system stores useful information and provides an easy way to display it through a mobile application designed for farmers. The mobile dashboard allows the farmer to observe live readings, to analyse historical trends, and to receive notifications when a pre-set threshold of water quality parameter has been exceeded, so farmers can act if necessary.

The Aqua Guard system is designed for expansion to allow for additional sensors (e.g, ammonia, turbidity, salinity) to be added to the system. It is easy to scale when a facility requires different things to monitor for their aquaculture operation. In effect, it allows the monitoring solution to grow as the aquaculture facility needs it, without having to redevelop an overall system, illustrating a sustainable and progressive choice for fish farming.

Iteration Based on Feedback from End-Users

First tests were conducted with aquaculture producers to more fully investigate the practicality, reliability, and usability of the system. Feedback gathered from this scope of trials indicated several priority areas for improvement:

- **Sensor Calibration:** The initial readings of the sensors recorded small discrepancies in terms of the professional-grade instrument readings. To address this inconsistency, we upgraded the firmware to include sensor calibration factors and also included advanced smoothing algorithms in the data. Following this, we saw a much-improved degree of accurate readings, so that the readings became more feasible for the farmers.

- **Offline Data Logging:** Farmers who worked in more remote or rural areas frequently had problems with unreliable internet coverage and could not monitor the water quality in real-time. Therefore, we added local data storage capability through the ESP32 module. This enables the system to store readings while offline, and the system can transfer those readings to the Blynk system as soon as a stable connection is re-established, allowing us to still trace the data and continue monitoring with little interruption.

- **Dashboard Layout:** Based on user feedback regarding the original mobile dashboard being too cluttered and challenging to navigate, we decided to completely redesign the layout to better design for users' experience. The new layout contains more descriptive labels and larger font sizes, repositioned separate boxes that show live data with historical data for each parameter. Our goal was to alleviate clutter and enhance readability and usability.

- **Alert Thresholds:** The alert returns had generic threshold values based on aquaculture management guidelines that did not consider the water quality conditions in the region of their farm. We redesigned the original threshold values to incorporate localized water quality data, providing relevant alerts and notifications for farmers to take timely action based on actual environmental conditions on each farm.

Appendix E: Ethical, Social, Economic, and Legal Considerations in Emerging Technologies

Importance of Ethics in the Development of Emerging Technologies

Using IoT-based monitoring technologies like Aqua Guard raises ethical issues related to data privacy, ethical security, and ultimately user trust. Under ethical principles of data use, it is an ethical responsibility to ensure that data for aquaculture farms, from water quality trends and operations approaches to sensor logging, is secured from data use (both malicious and benign) after data has been collected and communicated to the cloud. Moreover, users need to trust that researchers will communicate information to the end-user about how their data will be used, if it will be stored (and for how long), and how the data is protected from use beyond ethical data principles. Building trust to encourage long-term learning and adoption of the technology requires transparency in the use and design of the technology.

The designers of Aqua Guard took the ethical issues mentioned above into account. For example, Aqua Guard is designed with encrypted transmissions from sensors to the cloud, it does not allow any third-party access to sensitive information, and it allows users to control the changes to their user account, as well as the ability to change settings to their data collection device. Overall, the ethical design of Aqua Guard represents fairness (non-exploitative), respect for privacy (not co-opting data use from the user or abdicating data protection), and ensures that Aqua Guard works reliably.

Influence of Social, Economic, and Legal Factors

At a social level, Aqua Guard enhances healthier aquatic types of environments beneficial to farmers and additionally the local communities that depend on aquaculture for food, and as a source of income. The system is expected to help lower fish mortalities, help with sustainable farming practices, and promote a mindset of data-informed decision-making in traditionally low-tech farming.

At an economic level, the system intentionally uses low-cost microcontrollers and open source platforms to have affordable and scalable initial and operational costs. Since this technology is economical for small and medium-scale farmers, it provides an opportunity for farmers who may not otherwise be able to implement advanced monitoring systems because of economic barriers.

At a legal level, IoT-based solutions need to comply with local data protection laws, and sometimes environmental laws too. While Sri Lanka does not have IoT-specific legislation at this time, it still has generic cybersecurity and data privacy frameworks that cover IoT. The Aqua Guard system was developed by having these considerations in mind to secure the way we handled data, and considering legislation.

Regulatory Challenges in Keeping Up with Emerging Technologies

The major regulatory hurdle for bringing Internet of Things (IoT) technologies for aquaculture to life is the absence of standardized certification for environmental monitoring devices. As technology advances so quickly, regulators often seem to be playing catch-up, leaving both developers and end-users uncertain about whether to adopt a new, innovative solution. In more rural areas, issues of poor internet connectivity can also exacerbate the problems, as can a more widespread lack of knowledge about best practices when using new digital security features to maintain compliance with cybersecurity proposals.

In response to these pressing issues, Aqua Guard offers a strong brand solution based on the idea of modularity; this enables Aqua Guard to promote the adaptability of their devices while ensuring that it can easily refresh its devices as regulations change. They also offer their users awareness and training on how to operate and secure the systems in a way that enhances compliance and confidence in the technology's safety and reliability.

Defending Adoption Despite Ethical, Social, Economic, and Legal Challenges

There are some challenges to consider but benefits of IoT-based solutions such as Aqua Guard will far outweigh the cost of a few disadvantages. First, ethically, the system gives farmers timely, accurate data and informs them to better their livelihoods and increase food security for the end user. Second, socially, Aqua Guard is a sustainable aquaculture management system, meaning the actions taken by farmers have a positive outcome for the farmer and the fish, thus promoting a healthier ecosystem. Economically, the affordability and the efficiency of such a system means high customer interest, thus making the investment worthwhile where there is commonly a fast return on investment. Legally, the policies may still be under development; however, the technology can operate within guidelines for data protection and device safety, so by using these elements it promotes safe use of the technology, builds trust in the technology and protects user data.