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AquaLink in HAB Detection: Integrating IoT and 3D-Printed PETG for Monitoring Aquaculture Conditions Conducive to HAB

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ABSTRACT

Harmful algal blooms (HABs) pose a serious threat to aquaculture and environmental health, often resulting in considerable ecological and economic impacts. Conventional water quality monitoring techniques, often manual and time-consuming, are inadequate for the timely detection of conditions that promote HAB formation. To overcome these limitations, the AquaLink system was developed by integrating the Internet of Things (IoT) technology with 3D-printed polyethylene terephthalate glycol (PETG) enclosures, enabling scalable, real-time, and cost-effective monitoring of water quality. The system employs sensors to measure essential parameters, including atmospheric pressure, temperature, and turbidity, with data transferred through Raspberry Pi and ESP32 controllers to an IoT dashboard for real-time analysis and visualisation. PETG-based casings were combined with IoT-enabled sensors to improve durability and reduce biofouling in aquatic environments. Prototypes were tested across different water bodies to validate performance under real-world conditions. The results demonstrated that the system effectively provided real-time monitoring of aquaculture environments, allowing the early identification of HAB risks through continuous tracking of water quality indicators. Beyond its technical contributions, AquaLink offers societal benefits by serving as a low-cost, efficient tool that reduces fish mortality, limits environmental degradation, and enhances food security. The flexibility and scalability of the system make it applicable to small-scale and industrial aquaculture operations, fostering sustainable practices through advanced environmental monitoring.

Article information:

Keywords: Harmful Algal Blooms, Internet of Things, Aquaculture, Water Quality, Environmental Monitoring, Raspberry Pi, ESP32, Dashboard, ThingsBoard, Real-time Data, Sensor Integration, 3D Printing, PETG

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1. INTRODUCTION

Aquaculture has emerged as a potential means of addressing the increasing global demand for seafood. The productivity of aquaculture systems is closely linked to good water quality, which plays an important role in ensuring the health of cultured species [1], [2], [3], [4]. To promote growth, support sustainable aquaculture, and minimise disease outbreaks in cultured aquatic animals, parameters such as ammonia, dissolved oxygen (DO), nitrate, pH, and temperature must be maintained within the recommended ranges [3]. Conventional monitoring of these factors typically relies on manual sampling and subsequent laboratory testing, which are time-consuming [4]. In con-

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trast, real-time monitoring technologies provide rapid feedback, enabling farmers to respond promptly to environmental changes [1], [4], [5].

A major challenge facing aquaculture and natural ecosystems is the prevalence of harmful algal blooms (HABs). These blooms occur when colonies of algae, specifically phytoplankton, grow excessively in aquatic environments, typically under favourable environmental conditions of nutrient enrichment and higher water temperatures [6]. Some algae release toxins that endanger aquatic life, particularly fish and shellfish, and contaminate food and water sources. The economic impact of HABs on aquaculture can be severe, ranging from large-scale fish deaths to habitat loss and poor water quality [7]. Furthermore, HABs pose significant threats to human health, as exposure may lead to respiratory illness or toxin-related seafood poisoning through bioaccumulation [7].

Several parameters can be monitored to detect the onset of HABs. The presence of nutrients, with nitrogen and phosphorus being the most critical, is a key determinant of algal growth. An excess of these nutrients in the water can trigger algal blooms, a process known as eutrophication [6]. Eutrophication occurs when bodies of water become overly enriched with nutrients. Agricultural runoff, wastewater, and industrial effluents frequently elevate nutrient inputs, stimulating excessive algal and plant growth. The subsequent decomposition of algae consumes oxygen, destabilising aquatic ecosystems and creating dead zones where aquatic life cannot survive [8]. Water temperature is another critical factor, as warmer temperatures often promote the rapid proliferation of algae. Dissolved oxygen and pH levels are also indicators of water quality. During HAB events, oxygen levels can drop sharply as algae consume oxygen, especially at night [6]. Increased turbidity, or cloudiness of water, is another sign of a potential HAB, as blooms often lead to higher concentrations of algae and particulate matter, reducing water clarity.

The incorporation of Internet of Things (IoT) technologies into HAB detection and monitoring is becoming increasingly indispensable in modern aquaculture practices. These systems automate real-time monitoring of parameters such as DO, nutrient concentrations, and temperature, which are essential for predicting HABs [9]. Networks of sensors transmit data to cloud platforms for analysis, enabling early warnings and swift responses [10]. The effectiveness of IoT-based water quality monitoring systems can be further enhanced by integrating more advanced sensors and machine learning algorithms. These enhancements help predict and mitigate the risks of HABs, offering a scalable and cost-effective solution for aquaculture farmers [9]. This real-time, data-driven approach allows for early detection of environmental conditions conducive to HABs. As a result, it can potentially reduce adverse effects on aquatic life and water quality.

The IoT is defined as a network of interconnected devices capable of communicating and exchanging data via the internet [10]. In aquaculture, IoT solutions play a crucial role in automating water quality monitoring, which is essential for maintaining healthy aquatic ecosystems [1]. By deploying IoT-enabled devices, aquaculture farms can reduce manual labour and ensure more accurate and consistent environmental monitoring [2]. This section outlines the core components and functions of the AquaLink system. As an innovative monitoring tool, AquaLink is specifically designed to monitor water quality parameters in aquaculture environments. The system integrates IoT technology with 3D-printed polyethylene terephthalate glycol (PETG) casings to house and protect the sensors, as PETG is more durable than polylactic acid (PLA) and environmentally friendly, making it suitable for long-term use in aquatic conditions [11], [12]. The system uses various sensors, including the BME680 for air quality and gas measurements, a water temperature sensor, the DFRobot turbidity sensor to monitor water clarity, and a light sensor module to detect ambient light levels. By using the ESP32 microcontroller and a single-board computer (SBC) such as Raspberry Pi, AquaLink enables continuous data transmission to ThingsBoard, an IoT dashboard platform that visualises real-time data and provides actionable insights to farmers, helping them maintain optimal conditions for aquatic life. Although the current iteration of AquaLink does not directly measure HABs, it serves as a foundational framework that can be expanded to include sensors capable of detecting early signs of HABs.

As a starting point, this work focuses on designing and implementing a sensor array for monitoring general water quality parameters that help identify conditions favourable for HAB formation. For instance, AquaLink's temperature and turbidity sensors can detect rapid changes in water conditions that often precede algal blooms [5]. The system's scalability and flexibility allow for the integration of additional sensors in future versions to monitor nutrient levels and other factors directly linked to HABs. This potential for further development positions AquaLink as a valuable tool for sustainable aquaculture, where real-time monitoring of environmental factors can reduce the risk of HABs and their associated threats to food safety and productivity.

Raspberry Pi and ESP32 are two widely used platforms in IoT applications. The Raspberry Pi is an SBC that offers more computational power, making it suitable for data-intensive applications. Meanwhile, the ESP32, a low-power microcontroller, is favoured for its low power consumption and built-in Wi-Fi, making it ideal for remote monitoring. Both platforms support sensor integration for water quality monitoring. An important component of this study is the integration of ThingsBoard, an open-source IoT platform that supports data collection, processing, and visualisation through a customised dashboard. This enables users to monitor key water quality parameters in real-time, facilitating timely decision-making in managing aquatic environments. The technical contribution of this work lies in the development and deployment of an integrated, low-cost IoT-based monitoring system tailored for aquaculture. The AquaLink system combines real-time sensor data acquisition, threshold-based environmental risk evaluation, and durable PETG-based 3D-printed housings optimised for aquatic conditions. Although the current system does not implement machine learning for HAB prediction, it simulates bloom-prone environments in controlled settings and applies predefined parameter thresholds, such as turbidity and temperature, to indicate potential HAB risk. This serves as a critical first step towards future intelligent HAB detection. Unlike generic IoT applications, AquaLink is designed with affordability and modularity in mind, supporting deployments in diverse aquaculture settings with real-time data streaming, multi-controller compatibility, and scalability. The starting point of the research is discussed in [13].

Accordingly, this study adopts a structured approach to examine how IoT can be integrated with 3D-printed PETG technology for aquaculture water quality monitoring. Section 1 introduces the background, objectives, and concept of the AquaLink system for aquaculture water quality monitoring. Section 2 provides a literature review, discussing prior research on IoT and environmental monitoring technologies in aquaculture. Section 3 explains the methodology, detailing the system design, hardware components, sensor integration, and data collection process. Section 4 presents the results of the experiments conducted in various aquatic environments, assessing the system's performance. Section 5 discusses the key findings, comparing the effectiveness of the Raspberry Pi and ESP32 platforms and highlighting the advantages of using PETG 3D printing. Finally, Section 6 concludes the paper by summarising the contributions of the AquaLink system and proposing future improvements.

2. LITERATURE REVIEW

The design of sensors for water quality monitoring has been the subject of numerous theoretical studies, emphasising the need for accuracy, durability, and cost-effectiveness. An IoT framework enables real-time monitoring of aquatic environments using affordable sensors, with particular emphasis on selecting sensors that yield accurate measurements of parameters such as pH, temperature, and turbidity [2]. Additionally, the integration of multiple sensors into a single system allows for comprehensive monitoring of aquatic environments. For instance, an IoT monitoring system that combines various sensors to evaluate water quality for farmed aquatic species. It has been noted that the use of multiple sensors significantly improves the reliability of data collected, allowing for better decision-making in aquaculture management [14]. The materials used in sensor design also play a crucial role in ensuring long-term functionality in aquatic environments. Polyethylene terephthalate glycol is advantageous for sensor housings due to its chemical stability and water resistance, making it an ideal choice for underwater applications [15]. These studies underscore the importance of sensor selection and housing materials in the effective monitoring of water quality.

Raspberry Pi and ESP32 are two widely used controllers in IoT applications, each offering unique features and advantages. The Raspberry Pi is an SBC known for its powerful processing capabilities, making it suitable for data-intensive applications. It provides an excellent platform for building complex IoT systems, enabling users to run various applications and process large datasets [10]. However, its higher power consumption and more complex wiring requirements can be limiting factors in low-power, remote applications. The ESP32 microcontroller offers a cost-effective, low-power solution with integrated Wi-Fi and Bluetooth, making it highly suitable for remote monitoring tasks. It is favoured for its ease of use and flexibility in connecting multiple sensors without extensive wiring. In addition, the native support for this microcontroller for analogue sensors and lower power consumption makes it an ideal choice for IoT applications in environments such as aquaculture [3]. The choice between Raspberry Pi and ESP32 ultimately depends on the specific requirements of the application. For prototypes requiring significant processing power and complex data analysis, the Raspberry Pi is often preferred. In contrast, for applications that prioritise low power consumption and ease of integration with sensors, the ESP32 is a more suitable option.

The use of the IoT across various industries is widely accepted for enhancing automation and making decisions through real-time, data-driven insights [10]. In aquaculture, IoT systems have facilitated real-time monitoring of parameters, which is essential in the assurance of optimum conditions for aquatic life [2], [14]. This is supported by a study demonstrating that the IoT-enabled system can reduce costs by minimising human intervention in monitoring and detection processes. The system consists of sensors and equipment that work collaboratively to collect and transmit data on the temperature of water, pH, DO, and other important parameters [16].

Water quality is fundamental to successful aquaculture. More importantly, fluctuations in pH, DO, and temperature significantly contribute to stress and diseases, leading to high mortality among farmed species [16]. Traditionally, water quality monitoring has relied on manual sampling, which is labour-intensive and gives only a snapshot of conditions at that time. In contrast, automated and real-time monitoring systems enabled by IoT technology provide continuous data collection, which is crucial for ensuring timely interventions [17].

Several factors, including rainfall, temperature fluctuations, and water flow rate, can compromise the structure of the aquaculture system and disrupt the interrelations that maintain stability in the natural ecosystem if not properly managed [18], [19]. Careful attention to these factors, along with continuous monitoring, is critical to prevent environmental harm and ensure the long-term sustainability of aquaculture. In this context, an IoT-based environmental monitoring system equipped with multiple sensors should be used to integrate data, providing a comprehensive understanding of water quality and surrounding environmental conditions [15], [20].

Three-dimensional printing sensor enclosures using PETG filament offer an economical, versatile, and readily customisable solution. Polyethylene terephthalate glycol filament is well-suited for aquatic environments due to its durability, water resistance, and chemical stability [15]. Consequently, this material is commonly used to manufacture housings that protect sensors against water and biofouling threats on sensitive electronics. In aquaculture, conditions can vary significantly between sites. The ability to design and print custom parts reduces costs and allows for quick implementation of monitoring systems.

It is also important to emphasise that the long-term durability of 3D-printed sensor housings is crucial for effective environmental monitoring in aquaculture. While PETG is known for its excellent water resistance and chemical stability [12], the durability of 3D-printed PETG housings has been demonstrated in short-term studies. For instance, reports indicate that PETG sensor housings remain functional after two weeks of continuous submersion in aquatic environments [21]. However, to ensure reliable operation over extended periods, further research is necessary to evaluate the long-term durability and performance of PETG in real-world conditions.

Data on sensor fouling and maintenance requirements are essential for understanding the practicality of using PETG housings in long-term deployments. Studies have demonstrated that biofouling can significantly affect sensor accuracy and reduce lifespan if regular maintenance is not performed [22]. Regular cleaning and maintenance schedules are recommended to mitigate fouling and ensure accurate sensor readings. Additionally, investigating the effects of seasonal changes, such as temperature fluctuations and varying water conditions, can provide valuable insights into the performance and maintenance needs of PETG housings over time [21]. This information is vital for aquaculture farmers, as it helps them develop effective management strategies to ensure the longevity of monitoring systems.

Although PLA is a popular material for 3D printing due to its ease of use and biodegradability, it is generally not recommended for underwater applications such as those in aquaculture [23]. The material exhibits lower resistance to moisture and can degrade over time when exposed to water, leading to a decline in structural integrity and functionality [23], [24]. Studies have shown that PLA can become brittle and lose its mechanical properties after prolonged exposure to water, which can compromise the effectiveness of sensor housings [24]. Additionally, PLA is susceptible to temperature variations, particularly at elevated temperatures, where it may deform or warp [25]. In contrast, PETG provides greater thermal stability and is less prone to moisture absorption, making it a more suitable choice for aquatic environments [12], [26]. The chemical resistance of PETG also surpasses that of PLA, ensuring that the material maintains its integrity in the presence of various waterborne contaminants and pollutants commonly found in aquaculture settings [27].

3. METHODOLOGY

The integration of IoT devices and the AquaLink system with 3D-printed PETG enclosures enables comprehensive monitoring of aquaculture water quality by combining hardware and software to deliver real-time data on critical water quality parameters.

The system integrates advanced sensing technologies with cloud-based platforms for water quality monitoring and analysis, with its methodology centred on data evaluation, deployment, sensor selection, and system configuration.

The parameters selected for monitoring were chosen based on their relevance to aquaculture water quality and potential role in influencing environmental conditions that could contribute to HAB risks. External temperature and humidity offer insights into the surrounding conditions, which can affect water surface temperature. Atmospheric pressure helps detect weather changes that may impact nutrient inflow or water chemistry. Turbidity serves as a direct indicator of water clarity and the presence of suspended solids or algal particles. Meanwhile, water temperature is a fundamental factor affecting aquatic organism health, DO levels, and algal activity. Collectively, these parameters form a comprehensive dataset to assess environmental dynamics in aquaculture settings.

3.1 Controllers

Raspberry Pi 5 is one of the main processing units; it draws data from the attached sensors and packages it for transmission. On the other hand, ESP32 is an alternative controller that is low-cost, energyefficient, and features Wi-Fi and Bluetooth integration. It is also widely used among developers to send sensor data to the cloud and supports remote updates and configuration.

3.2 Sensor Integration

The system integrates several sensors for comprehensive water quality monitoring. The BME680 sensor measures air temperature, humidity, pressure, and gas levels in the surrounding environment, providing valuable data on atmospheric conditions. Water temperature is recorded using the DS18B20 sensor, which ensures accurate temperature readings crucial for maintaining optimal conditions in aquaculture. The system employs the gravity analogue turbidity sensor to assess water turbidity, which is a key indicator of water quality. For geolocation, the GPS NEO 6M module is used, enabling precise tracking of the sensor array's position in the water. Additionally, an analogue light sensor is included to detect ambient light levels, which can impact aquatic environments. Finally, the ADS1115 analogue-to-digital converter is utilised to facilitate the connection of analogue sensors to the Raspberry Pi, ensuring seamless data transmission and processing within the system.

Although this initial prototype does not include pH and DO sensors, these parameters are critical for detecting HAB risk conditions. Therefore, future versions of the AquaLink system will incorporate DO and pH sensors to provide a more comprehensive environmental profile and support predictive modelling of HAB events.

3.3 IoT Architecture and Cloud Integration

Sensor data are transferred to ThingsBoard, an open-source IoT platform deployed on the Microsoft Azure virtual machine. While ThingsBoard provides visualisation and real-time monitoring, Microsoft Azure supports processing and storage. Fig. 1 depicts the system structure, and Fig. 2 outlines AquaLink's flowchart, demonstrating how Raspberry Pi and ESP32 handle data prior to presentation on custom dashboards that display parameters including ambient temperature, gas level, turbidity, and water temperature.

Within the system architecture, real-time data transmission is achieved through the REST API provided by ThingsBoard. The dashboard was developed to support user-friendly interaction and real-time monitoring of environmental parameters. Azure, a global cloud computing platform created by Microsoft, provides infrastructure for managing, accessing, and developing applications and services for individuals, enterprises, and governments. As an open-source IoT platform, ThingsBoard is used to deliver real-time data visualisation through a customisable dashboard. This dashboard enables users to configure

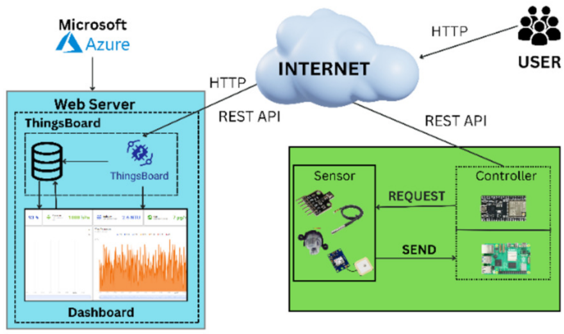


Fig.1: System architecture of AgriLink.

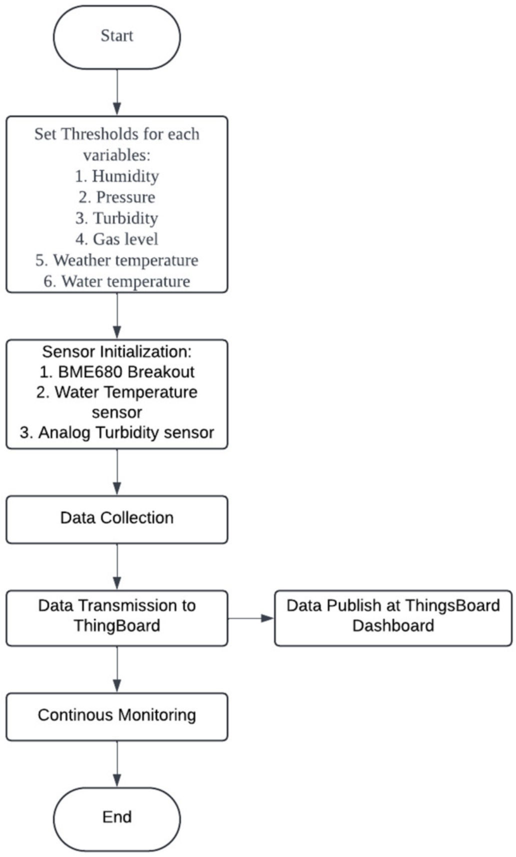


Fig.2: Flowchart of AquaLink.

parameter limits, activate alerts when thresholds are exceeded, and perform data logging for subsequent historical analysis. Python programming is the language used to write the scripts that run on the Raspberry Pi. The programme will control the acquisition of sensor data and their transmission. Communication between the Raspberry Pi and the cloud is facilitated using Python libraries. Conversely, C++ programming is used to program the ESP32. It is an object-oriented programming language that provides a clear structure to programmes and allows code to be reused, thereby reducing development costs.

3.4 Experimental Design and Data Collection

This study was conducted in four different environments to test the system's accuracy and efficiency. Prototypes were deployed in a fish pond, an aquarium, and a swimming pool for a 7-day period. Key variables included water temperature, turbidity, and environmental conditions such as air temperature and humidity. Several independent variables were selected, including the sensor types used in the system: the BME680, DS18B20, turbidity sensor, and GPS module. Additionally, the water conditions, both clean and turbid, were considered as independent variables. The dependent variables, representing data collected from the sensors, included surrounding air temperature, water temperature, turbidity levels, and GPS data for tracking the position of the sensor array in different aquatic environments. As no actual HAB events occurred during field deployment, a quantitative evaluation of detection accuracy, such as true positive rate or precision, could not be performed. Instead, the system was tested under simulated bloom conditions in a laboratory environment, where elevated turbidity and temperature levels were introduced. The system successfully flagged these conditions based on predefined thresholds, validating its ability to indicate environmental states conducive to HABs. Sensor performance, data consistency, and real-time transmission reliability were also evaluated across multiple aquatic environments. Future versions of AquaLink will incorporate AI-based detection models trained on real-world HAB datasets, enabling formal evaluation using precision, recall, mean, and F1 score.

The system was configured to collect and transmit sensor data at 10-min intervals to the ThingsBoard IoT dashboard. This interval was chosen to balance data resolution, power consumption, and network efficiency, making it suitable for real-world aquaculture monitoring, where rapid changes are uncommon. Although the hardware can sample at higher frequencies, a 10-min interval is sufficient to capture relevant environmental trends without overloading the system or exceeding storage capacity.

3.5 PETG 3D Printing

Custom CAD-designed sensor housings were printed using PETG filament. The material was chosen for its good water resistance and mechanical strength, ensuring the protection of sensors during submersion. The housings are designed to accommodate specific sensors and controllers, featuring watertight seals to prevent leakage. Several key factors make PETG an excellent choice for water quality measurement devices. Notably, PETG exhibits excellent resistance to moisture, different types of water, and many chemicals. This property is crucial for aquatic environments, where exposure to water and potential chemical pollutants is inevitable [11]. In addition, PETG can withstand long-term exposure to water without degrading, making it suitable for applications such as casings for sensors submerged in water [12]. It also resists acidic and alkaline environments, allowing the material to endure various water conditions without degrading or negatively impacting the water quality [26].

Besides, PETG stands out for its ability to resist ultraviolet (UV) radiation, which makes it highly durable for outdoor use [12], [27]. It does not undergo structural degradation when exposed to sunlight, although minimal colour fading may occur over time [27]. This property is vital for IoT devices intended to be placed on water surfaces for extended periods, where they are likely to be exposed to the sun in open water environments. Furthermore, PETG exhibits high impact resistance, which is advantageous for a floating or buoyant device that may experience physical stress from waves, debris, or even transportation. Its durability ensures that the casing can withstand rough handling and mechanical stress without cracking or breaking [11], [12]. In addition, PETG is relatively easy to print compared to more demanding materials such as acrylonitrile butadiene styrene or acrylonitrile styrene acrylate. This ease of printing allows the creation of intricate designs, enabling the casing to be customised to fit specific sensor and buoyancy requirements without the need for specialised equipment [12], [26]. It is also known for its good thermal stability, withstanding temperatures up to approximately 70–80 °C before deformation begins, making it highly suitable for environmental monitoring applications that may encounter temperature fluctuations [11], [27]. Its glass transition temperature, typically around 80 °C, ensures that the material remains stable and intact at moderate temperatures, which is the normal temperature encountered in outdoor aquatic environments [28]. From the AquaLink perspective, where temperature sensors are crucial, the stability of PETG across various temperatures ensures that the casing will not warp, crack, or degrade due to temperature changes [26]. This makes PETG ideal for use in temperate and tropical aquaculture environments.

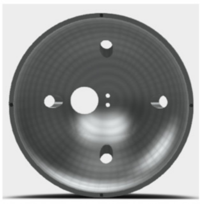
It is unsurprising that PETG is widely used in medical and food-safe applications due to its non-toxic nature. It complies with the Food and Drug Administration regulations, indicating that it does not release harmful chemicals into the environment, ensuring the safety of aquatic organisms and water quality [28], [29]. Moreover, PETG does not contain bisphenol A or other toxic compounds, making it safe for use in water quality monitoring devices without negatively impacting the surrounding ecosystem [12]. In addition, PETG is frequently used in medical devices because of its biocompatibility and chemical inertness, which further supports its use in environments where it may come into contact with sensitive aquatic life [11]. Its recyclability and widespread use in food packaging also underscore its environmental compatibility [26], [28].

These properties collectively strengthen PETG's suitability for buoyant IoT sensor casings, ensuring environmental safety and reliability across temperature variations. It is evident that PETG is among the best materials for outdoor and aquaculture IoT applications, as it ensures the longevity and reliability of the prototype, even when exposed to water, sunlight, and potential physical impacts.

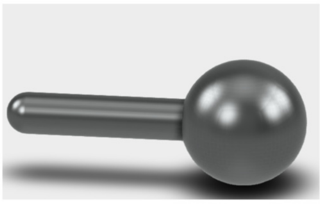
3.6 Development of 3D-Printed Casing

The 3D-printed casing used to house the sensors and controllers was developed through a step-by-step design and fabrication process. Fig. 3 shows the design of the casing created in Fusion 360, where Fig. 3(a) depicts the top enclosure that protects the controller and sensor modules from water splashes and direct sunlight. Additionally, Fig. 3(b) presents the bottom part of the enclosure, and Fig. 3(c) shows the extra support placed at the lowest section of the bottom part.

(a) Design of the top cover



(b) Design of the bottom cover



(c) Design of the extra support to keep the prototype floating

Fig.3: *3D modelling of the casing.*

Once the design was finalised, the slicing process was conducted using Bambu Lab Studio to prepare the model for printing. Polyethylene terephthalate glycol filament, chosen for its resistance to water and UV stability, was employed with the Bambu Lab P1P printer to produce the device casing. This approach enables rapid iteration and customisation of the casing to accommodate the specific environmental conditions of the aquaculture systems.

4. RESULTS

Preliminary testing of the AquaLink system was conducted in a controlled aquaculture environment to evaluate its performance in real-time water quality monitoring. The system collected several parameters, including water temperature, turbidity, and light levels. Although the BME680 sensor measured gas concentrations, these data were excluded from the analysis because gas levels are not considered significant indicators of HAB conditions in aquaculture.

4.1 Prototype Performance

Four prototypes, each equipped with identical sensors but utilising different controllers (Raspberry Pi and ESP32), were tested in various aquatic environments.

4.1.1 Prototype A: Fish Pond

This prototype utilised the Raspberry Pi and performed well; however, the complexity of the wiring and the requirement for analogue-to-digital converters introduced some noise into the data, slightly reducing accuracy. Table 1 shows the environmental and water quality data collected from Prototype A, which was deployed in a fish pond over a 7-day period.

Table 1: *Data collected from testing Prototype A.*

Day	External Temp. (°C)	Humidity (%)	Pressure (hPa)	Turbidity (NTU)	Water Temp. (°C)
1	29.3	78	1,011.6	2.5	26.5
2	30.1	75	1,012.2	2.8	26.8
3	28.7	80	1,010.7	2.7	26.2
4	29.8	76	1,011.9	2.9	26.6
5	30.5	74	1,012.5	3.0	26.9
6	29.0	79	1,011.4	2.6	26.3
7	30.2	77	1,012.1	2.7	26.7

The recorded data demonstrate the system's capability to consistently capture key environmental and water quality parameters relevant to aquaculture and potential HAB monitoring. External temperature and humidity remained within expected tropical ranges, with slight fluctuations reflecting daily weather conditions. Atmospheric pressure showed minor variations, indicating stable weather patterns during the test period. Turbidity levels remained relatively low, suggesting good water clarity, while water temperature showed a gradual increase consistent with external temperature trends. These consistent readings affirm the prototype's reliability in capturing real-time environmental dynamics, which is essential for establishing baseline conditions and detecting early signs of water quality deterioration in aquaculture environments.

4.1.2 Prototype B: Fish Tank

The ESP32-powered prototype demonstrated more stable and reliable performance, with fewer wiring issues and cleaner data collection. Due to its native compatibility with analogue sensors, the ESP32 offers a straightforward setup process that reduces the likelihood of errors. Table 2 presents the environmental and water quality data collected from Prototype

B, which was deployed in a fish tank containing fish over a 7-day period.

Table 2: *Data collected from testing Prototype B.*

Day	External Temp. (°C)	Humidity (%)	Pressure (hPa)	Turbidity (NTU)	Water Temp. (°C)
1	24.5	55	1,013.5	0.9	25.0
2	24.8	54	1,013.8	1.0	25.2
3	24.6	56	1,013.4	1.1	24.9
4	25.0	53	1,013.7	1.2	25.3
5	24.7	55	1,013.6	1.1	25.1
6	24.9	54	1,013.9	1.0	25.0
7	24.6	56	1,013.5	1.1	24.8

The data collected indicate stable environmental and water quality conditions under a different test setting compared to Prototype A. External temperature and humidity readings were notably lower, reflecting cooler and drier ambient conditions due to indoor placement. Atmospheric pressure remained consistently around 1,013 hPa, suggesting minimal weather interference. Turbidity values were relatively low, indicating clear water with minimal suspended particles, while water temperature showed little fluctuation, maintaining around 25 °C. The consistency across parameters highlights the reliability of Prototype B in capturing real-time data in stable environmental conditions and supports its suitability for continuous monitoring in less variable aquaculture settings.

4.1.3 Prototype C: Aquarium

Similar to Prototype A, this Raspberry Pi prototype also encountered issues with complex wiring and noise in data transmission, highlighting the limitations of the Raspberry Pi in environments with extensive use of analogue sensors. Table 3 shows the collected data from Prototype C, which was deployed in an aquarium without fish over a 7-day period.

Table 3: *Data collected from testing Prototype C.*

Day	External Temp. (°C)	Humidity (%)	Pressure (hPa)	Turbidity (NTU)	Water Temp. (°C)
1	25.1	57	1,014.0	0.8	24.7
2	25.3	56	1,014.2	0.9	25.0
3	25.0	58	1,013.9	1.0	24.6
4	25.2	57	1,014.1	0.9	24.9
5	25.4	56	1,014.3	0.8	25.1
6	25.0	58	1,013.8	0.9	24.8
7	25.1	57	1,014.0	1.0	24.7

The measured results of Prototype C indicate highly stable environmental and water quality conditions. The external temperature consistently remained around 25 °C with minimal fluctuations, while humidity remained steady between 56% and 58%. Atmospheric pressure was also consistent, averaging approximately 1,014 hPa. Turbidity values ranged narrowly, suggesting very clear water with minimal suspended matter. Water temperature showed only slight variation, remaining close to 24.8 °C.

4.1.4 Prototype D: Swimming Pool

The ESP32 prototype in this outdoor environment also outperformed its Raspberry Pi counterparts, consistently delivering accurate and reliable data with minimal interference. Table 4 presents the collected data from Prototype D, which was deployed in a swimming pool where the water was treated with chlorine.

Table 4: *Data collected from testing Prototype D.*

Day	External Temp. (°C)	Humidity (%)	Pressure (hPa)	Turbidity (NTU)	Water Temp. (°C)
1	28.4	70	1,012.0	1.2	27.1
2	29.0	68	1,012.3	1.3	27.3
3	28.2	71	1,011.8	1.4	27.0
4	28.8	69	1,012.1	1.3	27.2
5	29.1	68	1,012.4	1.4	27.4
6	28.5	70	1,011.9	1.3	27.1
7	28.9	69	1,012.2	1.2	27.3

Prototype D recorded relatively warm external temperatures with moderate humidity levels. Atmospheric pressure remained stable throughout the 7-day period. Turbidity values consistently ranged between 1.2 and 1.4 NTU, indicating low to moderate levels of suspended particles in the water, which could serve as an early indicator of environmental changes. Water temperature remained within a narrow range, suggesting stable thermal conditions in the monitored environment.

4.2 Sensors and Data Readability

The BME680 and DS18B20 sensors provide reliable air and water temperature data across all deployments. The turbidity sensor, essential for water quality monitoring, performed adequately in distinguishing between clean and turbid water; however, some noise was present in the Raspberry Pi setups due to analogue-to-digital conversion issues.

The system allowed real-time transmission of sensor data for pH, temperature, and DO into the ThingsBoard dashboard. It is capable of taking measurements with sensitivities of ±0.1 °C in water temperature, ±0.05 in pH, and ±0.1 mg/L in DO.

The sensors were well-protected by the 3D-printed PETG housings, with no signs of leakage or damage found after two weeks of continuous submersion.

4.3 Data Visualisation

The integration of ThingsBoard with Microsoft Azure enabled efficient real-time visualisation of water quality data. As illustrated in Fig. 4, the customised dashboards supported detailed monitoring, with trend graphs for parameters such as temperature and turbidity. The capacity of the system to process and store large amounts of sensor data in Microsoft Azure further demonstrated its scalability for broader applications.

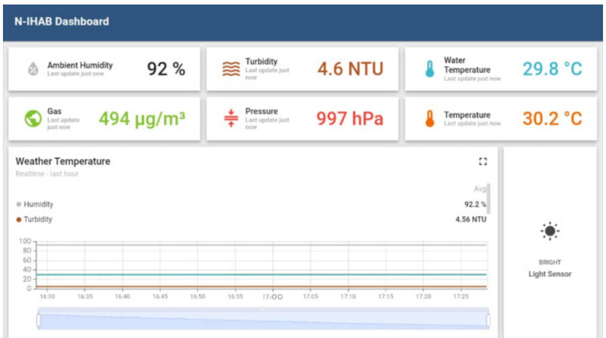


Fig.4: *ThingsBoard dashboard.*

ThingsBoard offers an intuitive, real-time visualisation interface with the ability to generate alerts and analyse historical data. Key parameter values can be set as threshold values, which trigger SMS or email alerts if these values go out of range.

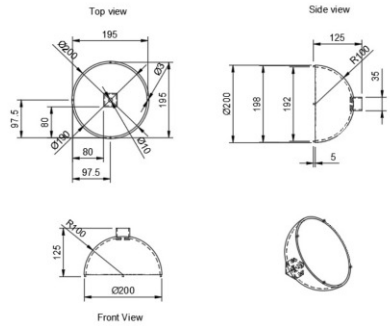
4.4 Results of 3D-Printed Structure

The 3D printing technique was employed to produce customised structures for housing the sensors and the controller. As demonstrated in the methodology, the design allowed for flexibility in shaping the casing to meet specific requirements for different aquatic environments. The use of the Bambu Lab P1P Printer provided several advantages, including automatic bed levelling and slicing optimisation, which enhanced the overall printing quality and precision.

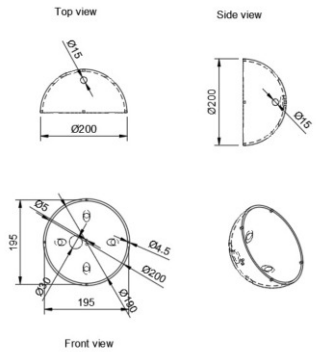
The design decisions for each AquaLink prototype directly influenced system performance during testing. Using PETG as the 3D printing material improved the casing's resistance to water and sunlight, helping maintain structural stability during extended outdoor deployments. In terms of hardware, the ESP32 was ideal for battery-powered applications due to its low power consumption, while the Raspberry Pi 5 supported more advanced processing tasks but required a stable power source and was more sensitive to heat.

Sensor placement and orientation inside the enclosure also influenced data accuracy, especially for turbidity measurements in flowing or shallow water. These design elements were refined through testing to achieve a balance among durability, measurement accuracy, and ease of installation across various aquaculture environments.

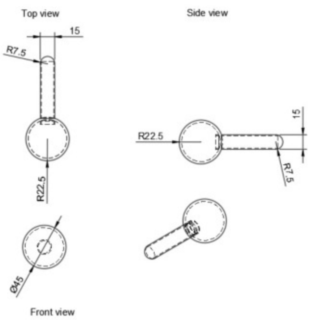
Fig. 5 illustrates the final measurements and isometric views of the 3D-printed sensor casing. Fig. 5(a) shows the measurement of the top of the casing, Fig. 5(b) shows the measurement for the bottom part, and Fig. 5(c) shows the measurement for the extra support. These measurements and views serve as a reference for future design improvements and customisation.



(a) Measurements of the top cover.



(b) Measurements of the bottom cover.



(c) Measurements of the extra support.

Fig.5: *Measurements and isometric views of the casing.*

Fig. 6 presents the complete printed structure of AquaLink as designed.

5. DISCUSSION

The comparison between the Raspberry Pi and ESP32 platforms highlights key differences in their suitability for environmental monitoring work. While the Raspberry Pi offers greater computational power, it lacks native support for analogue sensors and introduces complexity and noise, particularly in aquatic environments with varying turbidity levels. In contrast, the ESP32 proved to be more reliable, cost-effective, and efficient, particularly for remote, power-

Fig. 6: *3D-printed AquaLink.*

sensitive deployments. The results suggest that the ESP32 microcontroller is the more suitable platform for future iterations of work, particularly in environments requiring real-time, low-power data collection.

AquaLink has the highest potential to improve water quality monitoring in aquaculture. In turn, farmers receive these data and can respond promptly to any unfavourable changes. The integration of IoT and 3D printing makes the system flexible, scalable, and accessible even to small-scale farmers. The use of 3D-printed PETG is applied herein to provide a simple and low-cost approach for customising housing according to different environments and requirements.

A key advantage of the system is affordability. The use of a low-cost microcontroller (i.e., ESP32) in this design makes the entire system affordable for almost all categories of aquaculture. The system is also scalable because it is modular, making it easy to expand. Farmers can easily monitor multiple ponds or tanks from a single dashboard. AquaLink offers real-time monitoring by continuously collecting data, which enables constant observation of environmental parameters. This continuous monitoring helps reduce fish mortalities by minimising delays in taking corrective actions.

Although the AquaLink system did not detect actual HAB events in the field, simulated bloom scenarios were conducted in controlled environments to assess the system's ability to monitor environmental conditions associated with HAB formation. The system employs threshold-based logic, such as elevated turbidity levels, high temperatures, and reduced DO to indicate increased risk. This approach offers a practical early warning mechanism for aquaculture operators. In future research, the threshold-based system will be enhanced by incorporating machine learning models trained on both real-world and historical sensor datasets, enabling more accurate prediction of HAB events.

6. CONCLUSION

The AquaLink system has been successfully developed by integrating IoT technologies with 3D printing to create an affordable and durable platform for water quality and environmental monitoring in aquaculture. The current setup uses several sensors, such as the DS18B20 for measuring water temperature, a turbidity sensor to detect water clarity, and a light sensor to measure surrounding light levels. A BME680 sensor is also included to monitor air temperature, humidity, and gas levels, although gas data were not used in this study. All sensors are connected to ESP32 and Raspberry Pi 5 devices, which collect and transmit data to an online dashboard (i.e., ThingsBoard) for real-time display and monitoring.

Testing in a controlled environment showed that the system operates reliably and can continuously collect important parameters for aquaculture. The use of 3D-printed PETG housings helped protect the sensors, making the system more suitable for long-term use in water.

For future improvements, the system will be tested at real aquaculture sites to better understand its performance in natural conditions. Additional sensors, such as those for pH, DO, and possibly chlorophyll a, will be added to support the early detection of HABs. Furthermore, machine learning techniques will be explored to predict water quality trends and provide useful insights to aquaculture farmers. A comparison with existing commercial systems will also be conducted to evaluate the accuracy and practicality of AquaLink in real-world applications.

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and Roziawati Mohd Razali; data curation, Nik Nor Muhammad Saifudin Nik Mohd Kamal, Roziawati Mohd Razali, and Muhammad Farouk Harman.; writing—original draft preparation, Nik Nor Muhammad Saifudin Nik Mohd Kamal.; writing—review and editing, Nik Nor Muhammad Saifudin Nik Mohd Kamal, Ahmad Anwar Zainuddin, and Amir 'Aatief Amir Hussin.; visualization, Nik Nor Muhammad Saifudin Nik Mohd Kamal and Ahmad Anwar Zainuddin.; supervision, Ahmad Anwar Zainuddin, Amir 'Aatief Amir Hussin, and Normawaty Mohammad-Noor.; funding acquisition, Roziawati Mohd Razali, Ahmad Anwar Zainuddin, and Amir 'Aatief Amir Hussin. All authors have read and agreed to the published version of the manuscript.

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