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# Design and Implementation of an IoT-based Framework Device for Water Quality Assessment and Management

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ABSTRACT

Reliable water quality monitoring is essential for protecting ecosystems, safeguarding public health, and supporting sustainable water resource management. This study presents a modular Internet of Things (IoT)–based framework for real-time monitoring of water quality parameters, specifically pH and temperature, using an ESP32-32S micro-controller integrated with calibrated sensors. Measured data is transmitted *via* Wi-Fi to a cloud-based Blynk platform, enabling continuous visualization, logging, and rule-based alerting through remote interfaces. The system was validated through a seven-day field deployment, demonstrating stable operation, reliable wireless communication, and high measurement accuracy. Observed pH values ranged from 6.236 to 8.725, while temperature varied between 24.648 °C to 30.398 °C, remaining within the acceptable limits for Class II surface waters under the National Water Quality Standards (NWQS) of Malaysia. Comparative analysis showed close agreement between in-situ measurements and laboratory validation results. Experimental findings also revealed a clear relationship between temperature fluctuations and pH variation, highlighting the importance of continuous, high-resolution monitoring for capturing dynamic water quality behavior. The proposed framework is modular and scalable, allowing future integration of additional sensors and supporting data-driven decision-making for smart water quality management aligned with Sustainable Development Goal 6 (SDG 6).

***Keywords:*** Internet of things (IoT), Water quality monitoring, real-time sensing, ESP32 micro-controller, Smart water management.

## INTRODUCTION

The global water-pollution crisis continues to intensify as a result of rapid industrialization, urban expansion, and high-input agricultural practices, leading to the discharge of pathogens, nutrients, and toxic chemicals into surface and groundwater systems and compromising their suitability for domestic and agricultural use. Groundwater, often perceived as less vulnerable, is similarly affected by industrial effluents and agricultural run-off. Recognizing the escalating risks to public health and ecosystems, the United Nations World Water Development Report 2023 emphasizes the urgent need for improved and more responsive water quality monitoring systems (UNESCO, 2023).

Conventional monitoring approaches based on manual sampling and laboratory analysis are limited in their ability to capture rapid spatiotemporal variations caused by environmental dynamics and human activities. Their episodic nature, logistical constraints, and delayed data availability restrict timely intervention. In contrast, Internet of Things (IoT) technologies enable continuous, remote sensing and real-time analytics, supporting proactive decision-making and regulatory compliance (Bogdan et al., 2023). Beyond water quality assessment, IoT architectures have demonstrated adaptability across water-infrastructure applications, including pressure-based leak detection in supply networks (Malkawi et al., 2022).

Despite their potential, IoT-based monitoring systems face practical challenges related to sensor accuracy and drift, calibration robustness, data security, and the lack of standardized, field-validated design frameworks, with many reported implementations remaining site-specific and limited in generalizability (Nishan et al., 2024). Nevertheless, IoT-based systems provide higher temporal resolution and improved sensitivity for monitoring key parameters, such as pH, temperature, turbidity, and chemical constituents, enabling earlier detection of contamination in rapidly urbanizing regions (Amin et al., 2022). Modular IoT architectures further support scalable sensor integration, cloud-based analytics, and alert mechanisms, facilitating sustainable environmental management (Shanmugam et al., 2021).

In Malaysia, increasing water demand in regions, such as Peninsular Malaysia and Labuan, underscores the need for scalable and reliable monitoring solutions aligned with national regulatory requirements. Conventional techniques may fail to detect emerging microbial and chemical contaminants that pose public-health risks. In response, this study develops an IoT-based water quality monitoring system focused on real-time measurement of pH and temperature, designed in accordance with the National Water Quality Standards (NWQS).

This paper presents a generalizable ESP32 sensing framework that wirelessly transmits calibrated measurements to a cloud-based dashboard (Blynk) for real-time visualization and alerting. The framework defines sensor calibration procedures, acquisition frequency, power management, and scalability for future multi-parameter expansion. A pilot deployment at water retention ponds in UiTM Shah Alam demonstrates system feasibility under real-world conditions. By transitioning from periodic sampling to continuous monitoring, the proposed framework supports data-driven decision-making, enhances regulatory compliance, and contributes toward Sustainable Development Goal 6 (SDG 6), through improved water quality management across agricultural, aquacultural, rural, and urban environments.

## LITERATURE REVIEW

Water pollution remains one of the most pressing global environmental challenges, intensified by rapid industrialization, urban growth, agricultural run-off, and poor waste management. Contaminants, such as pathogens, heavy metals, pesticides, and excessive nutrients, increasingly enter natural water bodies, compromising ecological balance and water usability, particularly in developing regions where untreated sewage and agricultural chemicals pose serious risks to ecosystems and human health (Camara et al., 2019). In Malaysia, rivers and lakes play critical roles in domestic consumption, irrigation, and recreation, yet they are under increasing threat from pollution. National monitoring conducted in 2024 across 1,353 river water quality stations covering 672 rivers reported that 71% of them were classified as clean, 24% as slightly polluted, and 4% as polluted (Department of Environment, 2024). Water pollution in Malaysia originates from both point sources, including industrial discharges and sewage treatment plant effluents, and non-point sources, such as agricultural run-off, improper waste disposal, and fats, oils, and grease (FOG), which obstruct drainage systems and cause sewage overflows that contaminate rivers (WWF Malaysia, 2023). These impacts are further intensified by climate-change-induced flooding and land-use changes, including agricultural expansion and illegal logging, which have contributed to siltation and water quality degradation in areas, such as Sungai Lembing, Pahang, with consequences extending beyond environmental degradation to public health and economic stability.

Conventional water quality monitoring relies primarily on manual sampling followed by laboratory testing. Although effective under controlled conditions, these methods are inadequate for detecting sudden or short-term variations in water quality due to their intermittent nature, high operational costs, reliance on skilled personnel, and delayed feedback (Harmel et al., 2023; Sani et al., 2023). Episodic sampling often fails to capture transient pollution events occurring between sampling intervals, leaving potentially hazardous incidents undetected. The absence of real-time data acquisition and limited spatial and temporal coverage further restrict timely response, particularly during emergencies when delays in laboratory analysis can exacerbate public health risks (Abu Bakar et al., 2025). These limitations highlight the inadequacy of traditional monitoring approaches for dynamic and distributed water systems and emphasize the need for automated, adaptive solutions capable of continuous, high-frequency data collection across wide areas, as demonstrated in related water infrastructure applications, such as pressure-based leakage detection (Malkawi et al., 2022).

Advances in IoT technologies have transformed water quality monitoring by enabling continuous, real-time data acquisition through networks of sensors measuring parameters, such as pH, turbidity, temperature, dissolved oxygen, and chemical pollutants. These systems typically integrate micro-controllers or embedded platforms, such as ESP32, Arduino, or Raspberry Pi with wireless communication technologies including Wi-Fi, LoRa, or GSM, and cloud platforms for data storage, visualization, and analysis (Chandalwar et al., 2024; Yaacob et al., 2024). IoT-based systems support automated data acquisition, remote accessibility, and real-time alerting, with previous studies demonstrating effective monitoring and notification using low-cost sensor configurations (Sai et al., 2021; Chandalwar et al., 2024). Similar sensor-driven, real-time monitoring principles have been applied in other civil infrastructure domains, including pressure-based pipeline leakage detection (Malkawi et al., 2022), BIM-integrated real-time alert systems (Safayet et al., 2021), and model-based sensor fault-detection frameworks employing particle filtering and Mahalanobis distance (Li et al., 2019). Despite these advantages, IoT systems face challenges related to sensor drift, calibration errors, communication reliability, cybersecurity vulnerabilities, power consumption, and maintenance requirements (Sastrohartono et al., 2023; Pavithra and Pushpalatha, 2022; Lezzar et al., 2020). Nevertheless, reported accuracy levels of up to 97.5% for parameters, such as turbidity and total dissolved solids, demonstrate the feasibility of reliable IoT-based measurement when proper calibration and validation procedures are applied (Sastrohartono et al., 2023). Moreover, IoT-based water monitoring offers clear benefits in scalability, cost-effectiveness, and accessibility, particularly in remote regions, while integration with cloud computing and predictive analytics enables early warning systems and long-term trend analysis that enhance environmental protection and public health outcomes (Konde & Deosarkar, 2020; Abdulwahid, 2020).

Effective water quality assessment also requires alignment with regulatory frameworks. In Malaysia, the National Water Quality Standards (NWQS) established by the Department of Environment classify water bodies according to key physical, chemical, and biological parameters, defining acceptable thresholds for safe use in drinking, recreational, and agricultural contexts. The NWQS classifications and parameter limits are summarized in Table 1 (Yaakub et al., 2018). Complementing NWQS, the Water Quality Index (WQI) integrates multiple measured parameters into a single numerical indicator representing overall water quality status and suitability for specific uses, with classification ranges presented in Table 2 (Devi et al., 2016). Although most Malaysian water sources comply with the National Drinking Water Quality Standard (NDWQS), contamination remains a concern in rural and industrial regions due to agricultural run-off and inadequate treatment, with studies reporting the presence of pollutants, such as ammonia nitrogen and heavy metals, including lead and cadmium, in specific water bodies (Praveena et al., 2024; Abdullah-Al-Mamun & Idris, 2008; Yusry Che Ngah & Othman, 2011). The growing adoption of IoT for real-time monitoring is therefore increasingly important for maintaining compliance with these standards, as continuous data acquisition and automated alerts enable rapid corrective actions when measured parameters exceed allowable limits, provided that sensors are properly calibrated in accordance with Department of Environment requirements (Sharip & Suratman, 2017).

Despite numerous studies on IoT-based water quality monitoring, a significant research gap remains in the lack of standardized and validated framework designs that clearly define sensor integration, configuration protocols, data transmission strategies, and performance evaluation criteria. Existing implementations are often limited to small-scale, site-specific prototypes that lack scalability and consistency, frequently neglecting key factors, such as response time, energy efficiency, long-term stability, and compliance with local regulatory frameworks (Shao & Zhang, 2014; Rahu et al., 2023). This limitation is particularly critical in developing regions, where constrained infrastructure necessitates robust and adaptable monitoring solutions (Pranata et al., 2017; Barrington et al., 2014). While recent research has explored integrating IoT with machine learning to enhance predictive analysis and estimation of the Water Quality Index (WQI) (Rahu et al., 2023), such approaches depend on reliable baseline monitoring frameworks to ensure data quality. In response to these gaps, the present study proposes an ESP32 IoT framework using pH and temperature sensors for continuous, real-time water quality monitoring. The system is designed to comply with Malaysia’s National Water Quality Standards (NWQS) and validated through field testing at UiTM Shah Alam, offering a scalable and adaptable foundation for smart water quality management that can be extended to additional parameters and applied across diverse environmental contexts.

**Table 1.** The national water quality standards for Malaysia (Department of Environment, 2024)

| **Parameter** | **Unit** | **Class** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **I** | **II** | **IIB** | **III** | **IV** | **V** |
| Ammoniacal Nitrogen | mg/l | 0.1 | 0.3 | 0.3 | 0.9 | 2.7 | >2.7 |
| Biochemical Oxygen Demand | mg/l | 1 | 3 | 3 | 6 | 12 | > 12 |
| Chemical Oxygen Demand | mg/l | 10 | 25 | 25 | 50 | 100 | > 100 |
| Dissolved Oxygen | mg/l | 7 | 5-7 | 5-7 | 3-5 | <3 | <1 |
| pH | - | 6.5-8.5 | 6-9 | 6-9 | 5-9 | 5-9 | - |
| Electrical Conductivity* | µS/cm | 1000 | 1000 | - | - | 6000 | - |
| Total Dissolved Solid | mg/l | 500 | 1000 | - | - | 4000 | - |
| Total Suspended Solid | mg/l | 25 | 50 | 50 | 150 | 300 | 300 |
| Temperature | ∘ C | - | Normal +2∘ C | - | Normal +2∘ C | - | - |
| Turbidity | NTU | 5 | 50 | 50 | - | - | - |

**Table 2.** The water quality ranges

| **WQI Values** | **Water Quality Range** |
|---|---|
| 0-25 | Very Good |
| 25-50 | Good |
| 50-75 | Moderate |
| 75-100 | Bad |
| >100 | Very Bad |

## METHODOLOGY AND FRAMEWORK DESIGN

This study adopted a structured three-phase methodology to design, implement, and validate an IoT–based water quality monitoring system capable of continuous real-time measurement under field conditions. The methodology comprised (i) framework and system architecture design, (ii) hardware–software integration and system development, and (iii) field deployment with performance verification and validation. The overall workflow of the system development and evaluation process is illustrated in Figure 1.

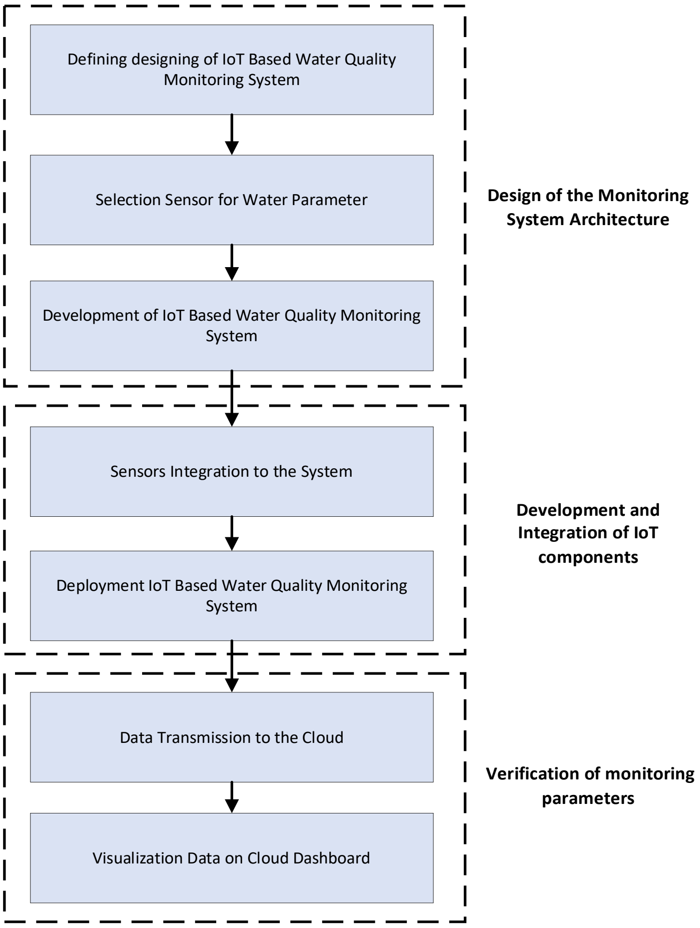

**Figure 1.** Flowchart of IoT-based water quality monitoring system development

### Framework Design of the IoT-based Water Quality Monitoring System

The initial phase centered on the establishment of a modular and scalable framework architecture capable of integrating both hardware and software components for continuous, real-time monitoring of key water quality parameters. The proposed framework was deliberately structured as a generic reference model intended to guide future researchers and practitioners in developing customized systems for diverse environmental contexts while maintaining compliance with regulatory standards, such as the National Water Quality Standards (NWQS) of Malaysia. The framework's architecture was therefore conceptualized to comprise four fundamental components:

1. Sensor Nodes (pH and Temperature Sensors) – for continuous water parameter data acquisition.
2. Processing Unit (ESP-32S Micro-controller) – for data collection, processing, and wireless communication.
3. Power Supply (Lithium-ion Power Bank) – for portable and autonomous power delivery.
4. Communication Network (Wi-Fi) – for real-time data transmission to a centralized dashboard.

The system design emphasized modularity to ensure scalability and flexibility. Although the prototype deployed in this study was limited to the measurement of pH and temperature, the architecture allows for the straightforward integration of additional water quality parameters, such as turbidity, dissolved oxygen, electrical conductivity, total dissolved solids, and ammonia nitrogen. These can be incorporated by expanding the sensor node layer and modifying the Blynk dashboard configuration without altering the core system logic. This design philosophy ensures that the framework remains adaptable to future research and industrial applications where a broader spectrum of water quality indices, such as the Malaysian Water Quality Index (WQI), may be required for comprehensive analysis and regulatory reporting.

The current configuration therefore serves as a proof-of-concept validation of real-time data acquisition, transmission reliability, and basic alerting based on NWQS thresholds, with the integration of multi-parameter modeling envisaged for subsequent development phases. The prototype system was implemented at a water retention pond located within the main campus of Universiti Teknologi MARA (UiTM) Shah Alam, encompassing an area of approximately 805.46 square meters, as shown in Figure 2. This field site provided an appropriate natural environment with varying physical conditions that facilitated assessment of the system's performance in dynamic aquatic settings. The overall interaction between the sensors, micro-controller, power module, and communication interface is depicted schematically in Figure 3, illustrating the logical flow of data from sensor acquisition to cloud-based visualization. The framework thus establishes a foundation for proactive water resource management consistent with Sustainable Development Goal 6 (SDG 6), which promotes access to clean water and effective environmental stewardship.


WATER RETENTION POND, UiTM SHAH ALAM

Perimeter
125.47 m

Area
805.46 m²

**Figure 2.** Aerial view of the water retention pond in UiTM Shah Alam

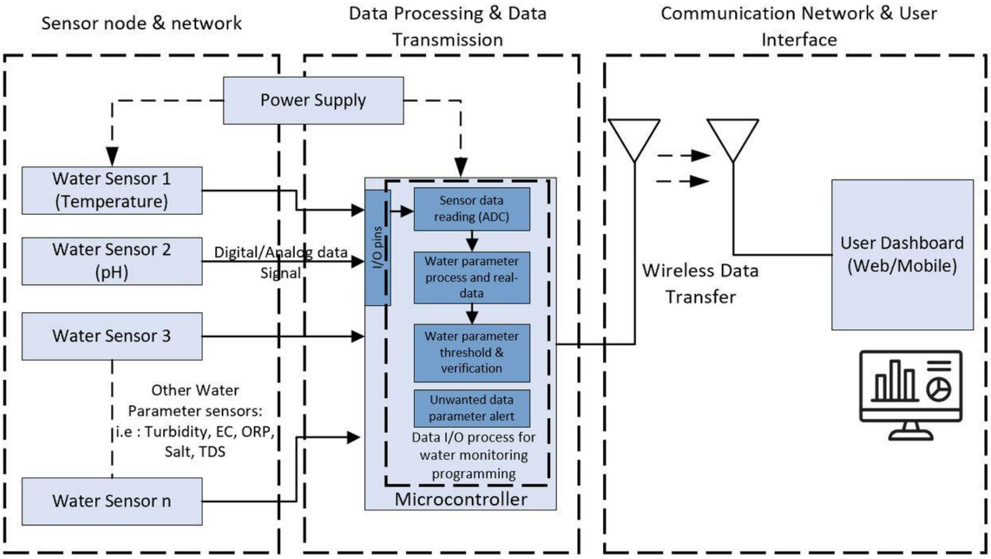

**Figure 3.** Block diagram of the IoT framework for water parameter monitoring

## Development of IoT Integration for Water Quality Monitoring

The second phase of the research focused on the practical realization of the conceptual framework through the integration of both hardware and software components into a fully functional IoT-based monitoring system capable of continuous data acquisition, wireless transmission, and real-time visualization. Central to this integration process was the incorporation of two primary sensors: The E-201-C pH sensor and the DS18B20 digital temperature sensor, both of which were interfaced with the ESP-32S micro-controller platform. These sensors were carefully selected on the basis of their stability, accuracy, and compatibility with IoT applications, ensuring that the resulting system could provide reliable data for long-term monitoring under variable field conditions.

The temperature and pH sensors, as illustrated in Figure 4 and Figure 5, respectively, were interfaced with the ESP-32S micro-controller to facilitate continuous data collection and transmission. The E-201-C pH sensor was connected *via* the analog input pin, with signal conditioning achieved through an onboard potentiometer circuit that ensured measurement stability and minimized electrical noise. Calibration of the pH sensor was performed using standard buffer solutions of pH 4, 7, and 10 to guarantee measurement accuracy within the acceptable range specified by the NWQS. The DS18B20 temperature sensor, which communicates through the OneWire digital protocol, was connected to the general-purpose input/output (GPIO) pins of the ESP-32S micro-controller, with an appropriate pull-up resistor incorporated to stabilize the digital output.

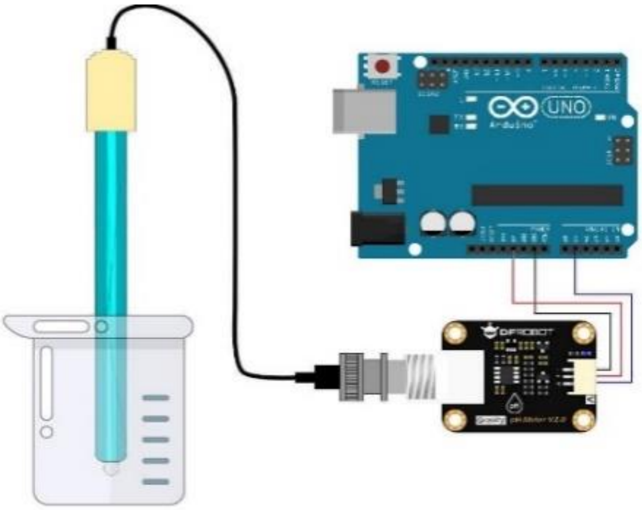

**Figure 4.** pH sensor setup (E-201-C)

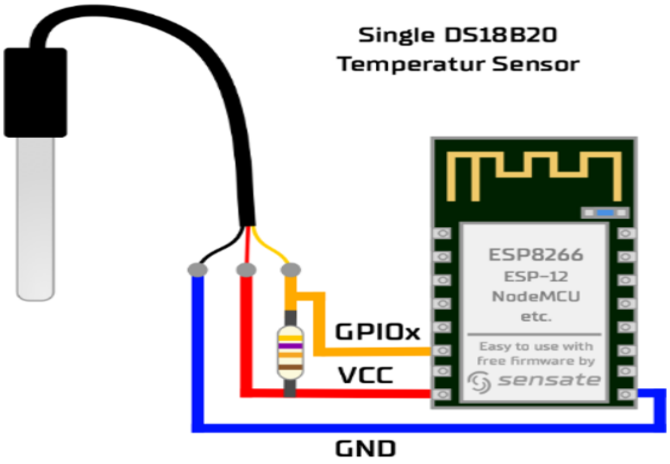

**Figure 5.** Temperature sensor wiring (DS18B20)

The entire wiring configuration and pin allocation for both sensors and supporting peripherals are summarized in Table 3, which lists the connection type, corresponding ESP-32S pin numbers, and their designated functional purposes within the monitoring system. The button input was programmed to serve as a manual control mechanism for initializing or resetting the system state, while Wi-Fi connectivity enabled real-time data transmission to the cloud-based Blynk platform for visualization and alerting.

**Table 3.** Connection details

| **Connection** | **Connection Details** | **ESP32** | **Purpose** |
|---|---|---|---|
| DS18B20 Temperature Sensor | OneWire protocol for data communication | GPIO 12 ('oneWireBus') | Temperature sensing |
| pH Sensor (Analog Input) | Analog input *via* potentiometer | PIO 34 ('POT PIN') | pH level measurement |
| Button for System Control | Connected to GPIO pin with pull-down resistor | GPIO 25 ('BUTTON PIN') | System state control |
| Wi-Fi Connectivity | Connects ESP32 to local Wi-Fi network | N/A | Enables communication with Blynk |

The coding and programming phase constituted a crucial element in this development process. The ESP-32S micro-controller was programmed using the Arduino Integrated Development Environment (IDE) with several essential libraries, such as *OneWire*, *DallasTemperature*, and *BlynkSimpleEsp32*. The custom-written program defined routines for data acquisition, time-averaged signal processing, Wi-Fi connectivity, and cloud communication. In particular, the system logic implemented periodic sampling of sensor outputs, data smoothing through moving-average filters, and basic rule-based evaluation of measurements against NWQS thresholds. When a parameter exceeded the defined range, the program triggered a visual or push-notification alert on the Blynk dashboard, thereby allowing immediate user response.

Prior to field deployment, comprehensive sensor calibration and validation were conducted to ensure the reliability and accuracy of the entire system. The pH sensor calibration process involved the use of buffer solutions under controlled laboratory conditions to determine the sensor's offset and gain coefficients, while the DS18B20 sensor output was cross-verified against readings from a certified mercury thermometer. Following successful calibration, the system was operated continuously over a seven-day period, during which the pH and temperature data was transmitted in real time to the Blynk cloud without interruption. The data was analyzed to identify diurnal fluctuations and assess the influence of environmental variations on water quality. The wiring arrangement connecting all system components, including sensors, power modules, and communication interfaces, is depicted in Figure 6, which presents the finalized circuitry layout adopted for deployment.

**Figure 6.** Wire arrangement for sensors (pH and temperature sensors)

This phase therefore culminated in the successful realization of a reliable and autonomous IoT-based water quality monitoring system that demonstrated accurate data capture, stable wireless communication, and efficient power management. The architecture was purposefully designed to remain flexible and extensible, permitting the incorporation of future sensor modules, different transmission protocols, and advanced analytic capabilities without requiring major hardware modifications.

### Verification of Monitoring Parameters and Framework Validation

The third and final phase involved the verification and validation of system performance under real-world environmental conditions to ensure both operational stability and measurement reliability. Multiple sensors were deployed across different points within the UiTM Shah Alam water retention pond to capture spatial variations in temperature and pH levels, thereby testing the robustness of the system's communication network and the repeatability of sensor readings. The IoT-based measurements were cross-checked against reference readings obtained from laboratory-grade instruments, allowing the calculation of calibration coefficients and error margins relative to the benchmarked standards defined by the National Water Quality Standards (NWQS).

Throughout the validation period, the system maintained consistent Wi-Fi connectivity and uninterrupted data transmission, confirming the dependability of the ESP-32S micro-controller in field conditions. Sensor readings exhibited minimal drift over time, indicating effective calibration stability and environmental resilience. To further improve measurement integrity, a simple validation layer was embedded in the program code, which automatically checked all incoming pH and temperature readings against predefined operational boundaries representing realistic environmental conditions of the monitored site. Any value outside these thresholds was flagged as invalid and displayed on the Blynk dashboard as a warning rather than an accepted data point.

In addition, the system continuously monitored repetitive identical readings across successive sampling cycles to identify potential malfunctions in either the sensor hardware or data communication link. When such anomalies were detected, an automated alert was generated to notify the user of possible sensor errors or disconnection events. This self-diagnostic capability effectively minimized the risk of false readings being interpreted as genuine changes in water quality. Future enhancements of the framework will extend this functionality through the integration of multi-sensor redundancy and adaptive recalibration algorithms, allowing the system to perform real-time correction of sensor drift and fault compensation without user intervention.

## RESULTS AND DISCUSSION

The experimental implementation of the proposed IoT-based water quality monitoring system was carried out at the water retention pond located within Universiti Teknologi MARA (UiTM) Shah Alam. The system was operated continuously for a period of seven days, during which the ESP32 micro-controller collected real-time measurements of pH and temperature through the integrated DS18B20 and E-201-C sensors, subsequently transmitting the data to the Blynk cloud platform for visualization, logging, and trend analysis. The overall performance of the system was evaluated in terms of measurement stability, data accuracy, wireless transmission reliability, and responsiveness to environmental variations, with the results summarized in Table 4. The measured pH values ranged between 6.236 and 8.725, while the temperature fluctuated between 24.648°C and 30.398°C, indicating that the monitored water body remained within the acceptable range for Class II surface waters according to the National Water Quality Standards (NWQS) of Malaysia.

**Table 4.** Result of pH and temperature changes over a 7-day period

| **Parameter** | **Range** |
|---|---|
| pH Value | 6.236 and 8.725 |
| Temperature (°C) | 24.648°C - 30.398°C |

To ensure a comprehensive evaluation of temporal variations, daily readings were recorded and analyzed, as detailed in Table 5 (Supplementary data), which presents the in-situ data collected over the monitoring period. The continuous data acquisition enabled the detection of both diurnal and inter-day fluctuations, which are typically overlooked in periodic manual sampling. The temporal relationship between pH and temperature values was further visualized in Figure 7, demonstrating distinct patterns that corresponded with environmental factors, such as solar radiation, ambient temperature, and biological activity. Parallel laboratory-based measurements were conducted under controlled conditions to validate the in-situ data, and the corresponding results are summarized in Table 6 (Supplementary data). Laboratory observations are shown in Figure 8, which display a similar trend to the in-situ data in Figure 7, revealing a high degree of correlation and confirming the consistency of the IoT-based system in capturing accurate and representative measurements.

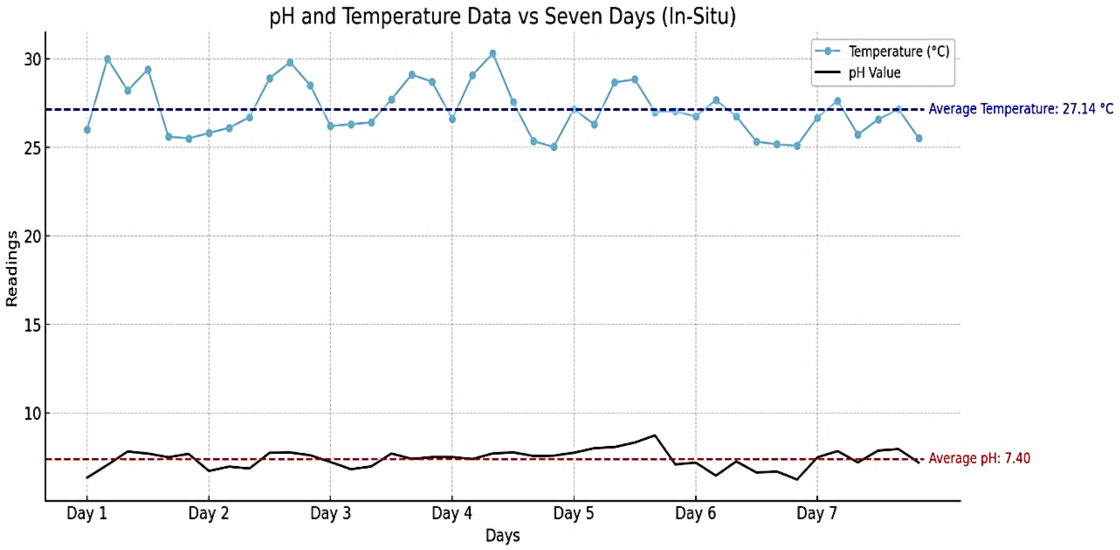

**Figure 7.** Graph of pH values and temperature versus day (in-situ)

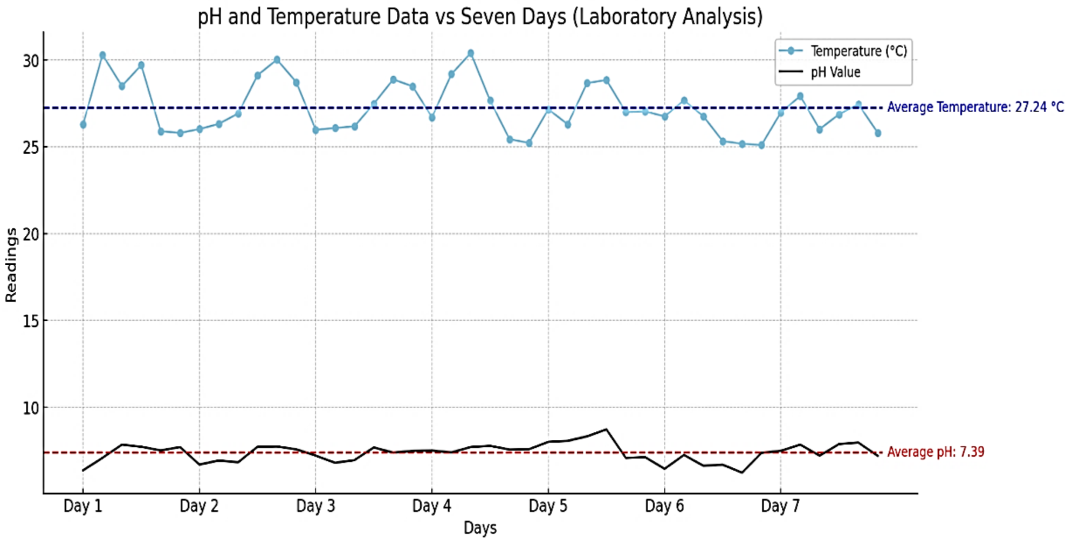

**Figure 8.** Graph of pH values and temperature versus day graph (laboratory analysis)

### System Implementation and Data Interpretation

The deployed IoT-based monitoring system demonstrated effective real-time data acquisition and transmission while maintaining operational stability under field conditions with variable environmental influences. Integration of the ESP32 micro-controller with the DS18B20 and E-201-C sensors enabled high-frequency sampling and continuous remote visualization *via* the Blynk application, allowing dynamic variations in water quality parameters to be captured and interpreted more effectively than with conventional manual sampling approaches.

The cloud-based Blynk interface provided intuitive access to live water quality data and supported automated, rule-based evaluation against the permissible ranges defined by the National Water Quality Standards (NWQS). When measured pH values deviated from the recommended range of approximately from 6.5 to 8.5, immediate alerts were generated, facilitating proactive identification of potential anomalies or contamination events and enabling timely response.

In addition to reliable pH and temperature monitoring, the system architecture demonstrated flexibility for future enhancement, including the integration of additional sensors and computation of composite indices, such as the Malaysian Water Quality Index (WQI). The stable OneWire communication for temperature sensing and optimized analog signal processing for pH measurement ensured accurate data conversion and transmission, confirming the system's suitability as a scalable and adaptable platform for continuous water quality monitoring applications.

### Analysis of pH and Temperature Trends

The data obtained over the seven-day monitoring period revealed a consistent correlation between temperature variations and pH fluctuations within the water body, suggesting that temperature exerts a significant influence on the acid-base equilibrium of the aquatic environment. The recorded pH range from 6.236 to 8.725 and temperature range from 24.648 °C to 30.398 °C are typical of tropical freshwater systems and conform to Class II water quality under Malaysian NWQS standards. As shown in Figure 7, both parameters displayed diurnal variations wherein pH levels tended to rise during daylight hours due to photosynthetic uptake of carbon dioxide by aquatic plants and algae, subsequently decreasing at night when respiration dominates. This cyclical trend indicates that the system successfully captured natural biochemical dynamics that would otherwise remain undetected by infrequent manual sampling.

The observed positive correlation between temperature and pH further reinforces the importance of simultaneous multi-parameter monitoring. As water temperature increased, pH values tended to rise slightly, reflecting a reduction in dissolved carbon dioxide concentration and a corresponding decrease in carbonic acid formation. This thermodynamic behaviour is consistent with the fundamental relationship between temperature and hydrogen ion concentration in aqueous systems, as discussed by Lakshmikantha et al. (2021). Consequently, even marginal temperature variations can substantially alter the ionic balance of water, affecting biological activity, nutrient solubility, and overall ecosystem stability. The results of this study therefore highlight the necessity of continuous, high-resolution monitoring to identify transient changes in water chemistry that could have long-term ecological implications.

Comparative analysis between in-situ and laboratory measurements (as presented in Figure 8) revealed close agreement, with average in-situ readings of pH 7.365 and temperature 27.069°C, compared to laboratory means of pH 7.239 and temperature 26.718°C. The minor discrepancies between the two datasets may be attributed to differences in environmental exposure during sample transport, as well as the controlled temperature and lighting conditions maintained in laboratory settings. Nonetheless, the strong correlation observed validates the precision and reliability of the IoT-based system, confirming that the measured values are both representative and accurate for field applications.

### System Performance Evaluation

Beyond measurement accuracy, the system exhibited robust communication stability and data integrity throughout the deployment period. The ESP32 microcontroller maintained uninterrupted Wi-Fi connectivity with negligible packet loss, while the Blynk cloud platform consistently logged data at predefined intervals. Periodic signal averaging implemented within the firmware effectively reduced noise, resulting in smoother trends without compromising real-time responsiveness, and the portable lithium-ion power supply supported continuous operation, demonstrating suitability for extended remote or off-grid monitoring.

Data reliability was further strengthened by an embedded validation mechanism that automatically identified unrealistic or repetitive readings indicative of potential sensor or communication faults. When such anomalies occurred, warning notifications were issued *via* the Blynk dashboard, minimizing the risk of misinterpretation due to hardware failure or environmental interference. Overall, the strong agreement between field and laboratory results confirms that the developed IoT-based water quality monitoring system offers a stable, accurate, and scalable solution for continuous environmental assessment, with a modular architecture capable of supporting future expansion and real-time decision support for water quality management.

## CONCLUSIONS

This study investigated the design, implementation, and field validation of an IoT–based water quality monitoring framework using real-time sensing of pH and temperature. The key conclusions are as follows:

1. An IoT-based water quality monitoring framework was successfully designed and implemented using an ESP32 micro-controller integrated with calibrated pH and temperature sensors, enabling continuous real-time data acquisition, wireless transmission, and cloud-based visualization through the Blynk platform.
2. Field deployment demonstrated stable system operation, reliable wireless connectivity, and high measurement accuracy, with close agreement observed between in-situ measurements and laboratory-based validation results.
3. The integration of real-time monitoring with rule-based alert mechanisms enabled immediate identification of deviations from the National Water Quality Standards (NWQS), effectively overcoming the limitations associated with conventional manual sampling.
4. Experimental results confirmed a clear relationship between temperature fluctuations and pH variation in the monitored water body, highlighting the importance of continuous, high-resolution monitoring for accurately capturing dynamic water quality behavior.

**Conflict of Interests**

The authors declare no conflict of interests.

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