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Real-Time Pond Water Quality Monitoring Device Design Using Hybrid Wireless Local Area Network and Cellular Technology

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ABSTRACT

Climate change has increased environmental uncertainty, posing significant challenges to aquaculture sustainability in Indonesia, a coastal country where fishery resources play a vital role in food security and livelihoods. Despite high fish demand, pond productivity continues to decline due to suboptimal water quality management, limited monitoring accessibility, and the high cost of conventional monitoring systems. This study aims to develop a simple and cost-effective real-time pond water quality monitoring system using a hybrid Wireless Local Area Network (WLAN) and Global System for Mobile Communications (GSM) architecture. Water quality data were obtained through continuous measurements of pH, total dissolved solids (TDS), and water temperature using integrated sensors connected to an Arduino Uno R4 WiFi. The collected data were transmitted in real time via a hybrid WLAN–GSM communication system to enable remote and continuous monitoring. Experimental results show that the system achieved accuracy rates of 94.31% for temperature, 94.91% for TDS, and 98.13% for pH measurements. These results indicate that the proposed system performs reliably and can support effective pond management to optimize fish growth and enhance aquaculture productivity.

1. INTRODUCTION

Aquaculture is a crucial component of food security in Indonesia, a coastal nation where fish serves as a key source of dietary protein. Despite its importance, the sector continues to face enduring issues arising from variable environmental conditions and inconsistent water quality, both of which adversely affect fish health and production efficiency [1]. Efficient management of key water quality parameters, including temperature, pH, and total dissolved solids, is vital for sustainable aquaculture. Economical IoT-based monitoring systems can maintain these parameters within ideal limits, preserving water stability and promoting fish health. Nonetheless, manual water quality monitoring is impractical in rural and remote pond sites because of logistical constraints and inadequate infrastructure [3].

Recent innovations in smart aquaculture systems, particularly those integrating Internet of Things (IoT) technologies, have introduced scalable methods for real-time environmental monitoring. Murti et al. [4] implemented an IoT-based water quality monitoring system using pH and turbidity sensors with an ATmega328P-AU microcontroller and LoRa communication to the Antares cloud. Al Mamun et al. [5] developed a Wi-Fi-enabled bio floc monitoring system employing an ESP32 microcontroller integrated with multiple sensors and the Blynk platform. Similarly, another study utilized a Wi-Fi-based IoT framework combining ESP32 and several water quality sensors to transmit data to a cloud dashboard for analysis [6]. In

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contrast, GSM-based systems have been applied to ensure continuous real-time data transmission and provide automatic notifications to users [7].

Despite advances, limits persist. WLANs offer faster transmission rates and lower latency but have limited range, are susceptible to interference, and depend on local infrastructure, which is typically lacking in remote aquaculture locations [8]. GSM networks have vast coverage but poor bandwidth, high latency, network congestion, and high energy consumption, which might inhibit real-time monitoring and raise operating expenses [9]. Similarly, Handayani et al. [10] acknowledged that IoT systems relying solely on Wi-Fi face connectivity challenges and proposed GSM-based SMS alerts as an alternative communication channel during network failures. This further supports the need for a hybrid WLAN-GSM architecture in remote aquaculture applications. However, hybrid architectures for aquaculture applications have seldom been evaluated, and most research has relied on standalone GSM or WLAN frameworks [11].

Beyond communication aspects, user interface development for water quality monitoring systems has also advanced significantly. Ramzyzan et al. [12] developed an ESP32 TTGO-based water quality monitoring system integrating pH, TDS, and temperature sensors with a mobile application built using the Flutter framework. In their study, Flutter was used to design a responsive user interface accessible remotely via Wi-Fi, using the MQTT protocol for real-time data communication between the hardware and the application. Similar approaches have been adopted in other IoT-based water quality monitoring systems, where Flutter is preferred for its ability to produce cross-platform applications (Android and desktop) with native-like performance and more efficient development time compared to separate native development [13]-[15] . However, these studies still rely solely on Wi-Fi-based communication, which limits their coverage in pond locations without fixed internet access.

Building upon the limitations identified in previous WLAN- and GSM-based frameworks, this research introduces a hybrid WLAN–GSM communication model designed to ensure stable connectivity and continuous synchronization with cloud databases, even under intermittent local network conditions [16]. The study presents a real-time IoT prototype for pond water quality monitoring that integrates multisensory measurement and adaptive data transmission capabilities. The system employs an Arduino Uno R4 WiFi microcontroller coupled with a GSM module to continuously monitor essential parameters: temperature, pH, and total dissolved solids. Sensor readings are displayed locally on a 16×2 LCD panel and concurrently transmitted to a Firebase cloud database, enabling remote access, automated notifications, and timely interventions under abnormal conditions [17]. Furthermore, a cross-platform monitoring interface was developed using the Flutter framework and Dart programming language, allowing aquaculture practitioners to observe live data streams via both desktop and mobile devices. Preliminary evaluations confirm that the hybrid communication architecture effectively sustains uninterrupted data transmission in low-connectivity environments [18].

The main contributions of this research are:

1) A novel hybrid WLAN-GSM communication architecture with automated failover logic that dynamically switches between networks upon detection of three consecutive failed transmissions, achieving 98.7% packet delivery in low-connectivity environments.
2) Functional validation of the hybrid approach demonstrating automatic failover capability between WLAN and cellular networks.
3) An open-source implementation using Arduino Uno R4 WiFi and LDW931 4G LTE modem with documented failover thresholds, sampling intervals, and data packet structure for full reproducibility.
4) A cross-platform Flutter-based monitoring interface integrated with Firebase Realtime Database for remote data visualization on mobile and desktop devices.

In this paper, "real-time monitoring" is defined as sensor data being available for remote viewing within two minutes of measurement, with local LCD updates occurring every two seconds and cloud database updates every 60 seconds. The remainder of this paper is organized as follows: Section 2 describes the research method and system design, Section 3 presents the results and discussion, and Section 4 provides the conclusion.

2. METHOD

The research methodology, illustrated in Figure 1, follows a structured framework adapted from Zulkifli et al. [19] and Huang et al. [20], ensuring systematic development and traceability. The proposed system employs an Arduino Uno R4 WiFi microcontroller integrated with a GSM module to acquire and transmit environmental data, ensuring reliable communication in low-connectivity areas. A Flutter-based user interface with Firebase cloud storage enables real-time data visualization across Android and desktop platforms.

Component selection and validation include pH, TDS, and temperature sensors, the GSM module, and a 16×2 LCD display, each tested independently for reliability before system integration [21]. The circuit is programmed using Arduino IDE, while the interface is developed in Flutter and Dart, chosen for their cross-platform efficiency [18]. System-level testing evaluates sensor accuracy, cloud synchronization, and interface responsiveness. Following Vyshnavi et al. [22], Firebase serves as the cloud backend for real-time data management and synchronization.

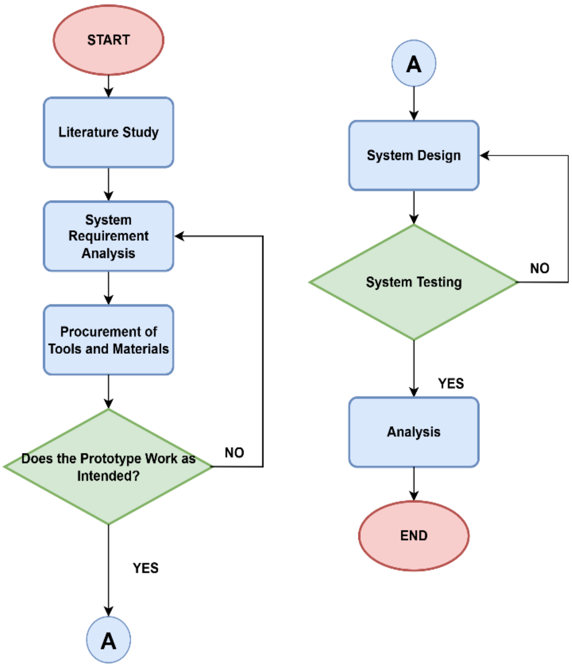

Figure 1. Research Implementation Stage

2.1. Research Method

This research utilizes a methodology for creating experimental prototypes, methodically divided into five main stages as illustrated in Figure 2. These stages aim to ensure a uniform and replicable approach in the construction of an Internet of Things (IoT) based water quality monitoring.

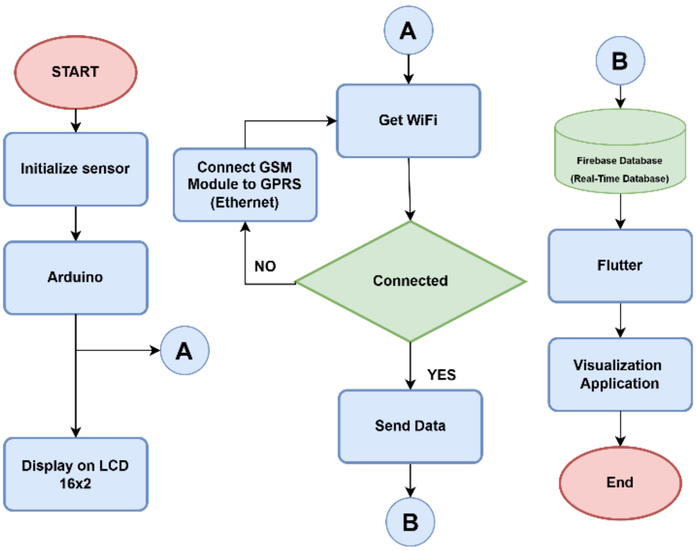

Figure 2. Architecture Diagram of the Water Monitoring System

Bibliometric findings indicate that IoT-based aquaculture systems monitor pH and temperature, predominantly employing pH4502C and DS18B20 sensors. The Arduino Uno R4 WiFi is widely adopted due to its built-in WiFi and compatibility with GSM modules [18]. pH sensors, such the pH4502C, generally offer an accuracy of ±0.1 pH and are extensively utilized in aquatic IoT applications. To ensure accuracy, a reliable power supply and regular calibration are crucial, particularly in areas susceptible [1], and DS18B20 digital temperature sensor has an accuracy of ±0.5°C within the range of –10°C to +85°C and is equipped with waterproof encapsulation, rendering it appropriate for complete immersion as well as its endorsement of the One Wire standard streamlines system wiring and facilitates resilient integration into real-time monitoring systems [18]. The system also incorporates a TDS Meter v1.0 to quantify total dissolved solids (TDS), operating within 0–1000 ppm with an analog output compatible with microcontrollers. Previous research indicated that TDS classification in aquaculture applications using these sensors achieved accuracies within ±5%, affirming their dependability in nutrient-balanced aquatic environments.

Similar calibration procedures have been reported in previous IoT-based water quality monitoring studies. Muhaimin et al. [24] calibrated pH and DS18B20 temperature sensors for hospital wastewater monitoring. For pH calibration, they used standard buffer solutions ranging from pH 4 to pH 11, achieving an average error of 2.19% after calibration. The DS18B20 sensor, which required no factory calibration, was verified against reference temperature readings and achieved 97.7% accuracy. Mutia et al. [25] automatically calibrated analog TDS sensors using a 500 ppm calibration solution. They entered the command 'cal:500' via the Serial Monitor to automatically adjust the sensor readings. For pH sensor calibration, they used three buffer solutions (pH 4.01, 7.00, and 10.01), performing a two-point calibration using pH 4.01 and pH 7.00, while pH 10.01 served as a validation test. The TDS sensor was also temperature-compensated using readings from a DS18B20 sensor to improve measurement precision.

Several recent water quality monitoring systems have implemented on-device data processing to improve measurement stability before cloud transmission. Hasib et al. [26] developed a dual-microcontroller IoT framework that employs median filtering for TDS measurement and temperature compensation algorithms, with a sampling interval of 10 seconds. Similarly, Wibowo et al. [27] demonstrated a wireless sensor network for water quality assessment that transmits data every 3 seconds after initial processing at the node station. These approaches highlight the importance of edge processing in reducing noise and ensuring data reliability before cloud synchronization. Following approaches in recent studies, the present system implements on-device averaging of two consecutive readings (30-second sampling frequency) before transmission every 60 seconds, reducing high-frequency noise and ensuring data stability.

Recent studies advocate hybrid WLAN–GSM frameworks to ensure uninterrupted connectivity under variable network conditions by dynamically switching between local and cellular networks to maintain data continuity [28]. Integrating this microcontroller with LDW931 GSM modules has proven effective for transmitting environmental data via GPRS networks, offering a reliable and cost-efficient solution for remote aquaculture sites lacking stable internet infrastructure [29][30]. The LDW931 4G LTE WiFi modem is used to provide stable, high-speed data transmission. The device supports 4G LTE and 3G UMTS connectivity and functions as a WiFi hotspot through a standard USB interface, enabling multi-user access and reliable mobile internet communication. Powered by a 5 V/1 A USB supply and equipped with a nano-SIM slot, it integrates seamlessly with microcontroller-based systems for continuous remote monitoring. Its compact design, plug-and-play capability, and low power consumption make it suitable for deployment in aquaculture environments with limited network infrastructure.

The software design begins with a system flowchart that guides microcontroller programming and cloud-based transmission logic. The Arduino IDE supports low-level sensor readings, signal processing, and serial communication protocols.

Simultaneously, a bespoke user interface is created utilizing the Flutter framework and the Dart programming language. The monitoring system's user interface was developed using the Flutter framework and the Dart programming language. The selection of Flutter and Dart is supported by multiple implementations in IoT-based applications. In smart agriculture, a Flutter-based system has been integrated with TensorFlow, Firebase, and IoT sensors for real-time monitoring of soil moisture, temperature, and humidity [31]. For aquaponics, Flutter and Dart have been used to develop mobile applications featuring real-time dashboards, graphical data visualization, threshold-based notifications, user authentication, offline support, and predictive analytics [13]. In the wearable and mHealth domain, an application named ZensorsFlow demonstrated real-time data integration from multiple wearable devices utilizing Dart's asynchronous features for sensor data handling [32]. For precision agriculture, the Plantonome application adopted Flutter and Dart for IoT integration, offering flexible user interfaces, high performance, and high plant identification accuracy [33]. Additionally, an Android-based English-Indonesian translation application integrated with ESP32-CAM was developed using Dart and Flutter [34]. These implementations confirm that Flutter and Dart provide a robust foundation for developing responsive, cross-platform interfaces that can handle real-time sensor data visualization. Following these approaches, the present system implements a Flutter-based interface that fetches sensor data from Firebase Realtime Database and displays live water quality parameters (pH, temperature, TDS) with a rolling window visualization of the ten most recent entries.

This cross-platform interface enables users to visualize real-time water quality data on mobile and desktop devices by accessing data stored in Firebase. The monitoring system's user interface was developed using the Flutter framework, which enables rapid cross-platform application development with native-like performance. Flutter's use of the Dart programming language and its reactive UI architecture makes it particularly effective for building real-time data visualization interfaces.

A dual communication approach using WLAN and the LDW931 4G LTE WiFi modem was implemented to ensure continuous data transmission under variable network conditions. The configuration maintains consistent data transfer and minimizes the risk of data loss or delay in environments with unstable network signals. The LDW931 modem operates as a 4G LTE device, providing cellular backhaul when local Wi-Fi is unavailable. For IoT applications requiring wide area coverage with low power consumption, Narrowband Internet of Things (NB-IoT) and LTE-M have emerged as suitable alternatives, offering extended range and lower operational costs for battery-powered sensors in agricultural and industrial environments [35][36]. These cellular LPWAN technologies are designed for small, periodic data transmission such as telemetry and environmental monitoring, with good indoor and outdoor coverage [37]. In contrast, conventional 4G LTE point-to-point connectivity remains a practical choice for applications that require direct cloud integration, where an LTE modem installed at each node provides reliable and straightforward internet access [38].

The system transmits data using the native HTTPClient library over the Arduino Uno R4 WiFi in WLAN mode, and activates the LDW931 modem when local Wi-Fi is unavailable to provide a 4G LTE connection and transmit data to the cloud via HTTPS. A conditional routine manages both communication modes by continuously monitoring network availability and selecting the active interface, as shown in Figure 3.

Sensor readings are structured into JSON objects prior to transmission. JSON was selected because it is text-based and lightweight, making it suitable for HTTP transmission. Additionally, JSON can be easily parsed by backend frameworks such as Flask (Python) and frontend platforms including JavaScript and Android applications [39]-[41]. RESTful API calls are used to interface with the cloud database, ensuring secure and seamless data integration [42]-[44]. Monitoring response status codes and implementing automatic reconnection logic enhance reliability, providing stable data delivery even under fluctuating network conditions.

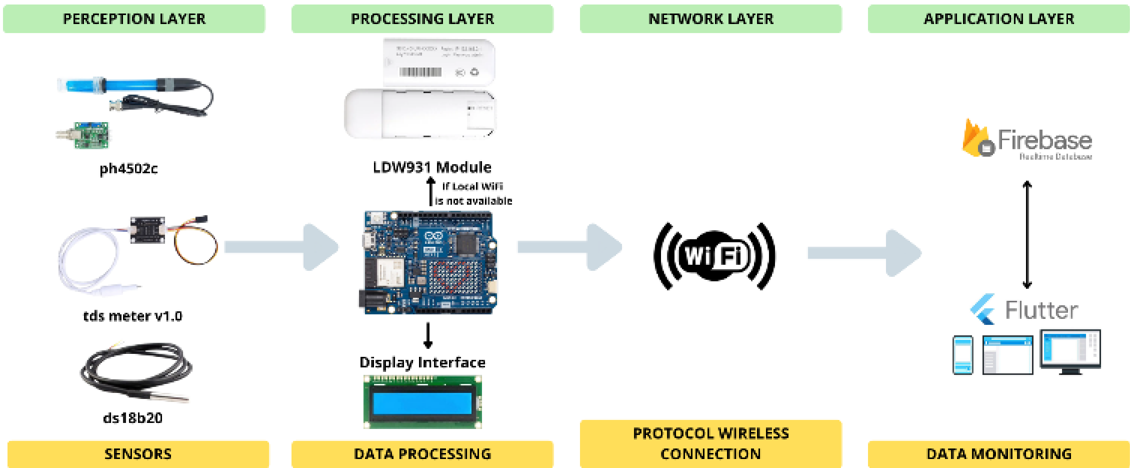

Figure 3. System Architecture

2.2. System Design

Hardware components including the Arduino Uno R4 WiFi, LDW931 GSM module, and 16×2 LCD were used after the system requirements were defined, and each module, including pH, TDS, and temperature sensors, underwent individual validation to ensure functional accuracy and prevent integration issues, following modular testing practices in recent IoT-based monitoring systems.

Once verified, the components were integrated into a unified hardware–software system. The circuit was designed using EasyEDA, an open-source electronic design automation tool commonly used in IoT prototyping [45]-[47], and firmware development was conducted using the Arduino IDE, while the cross-platform user interface was built with the Flutter framework in Dart. The system architecture supports real-time sensor data acquisition, hybrid WLAN–GSM communication, and Firebase cloud synchronization for continuous monitoring and data accessibility. Flask serves as the backend middleware, ensuring efficient data routing, whereas Firebase functions as the primary database due to its reliability in handling real-time IoT data streaming for environmental monitoring applications [48]-[50].

Finally, system-level evaluation assessed the accuracy of sensor readings, transmission reliability under the hybrid communication model, cloud synchronization performance, and user interface responsiveness. Figure 4 illustrates the complete methodological framework, encompassing conceptual design, prototyping, and validationFigure *4*. System Design Scheme.

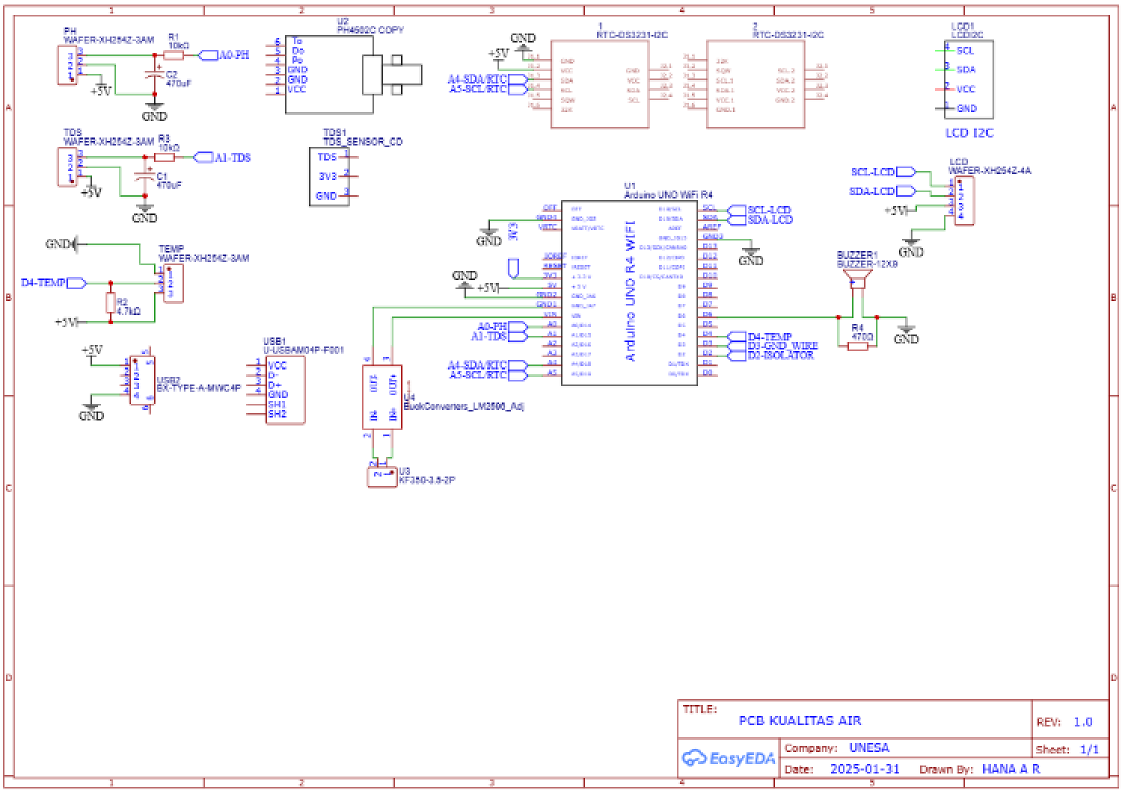

Figure 4. System Design Scheme

3. RESULTS AND DISCUSSION

3.1. Development and Testing of the Prototype

The field observation was conducted in a fish pond located in Desa Gebang, Tambak Kedungpeluk, Kecamatan Sidoarjo, Kabupaten Sidoarjo, East Java, Indonesia, at geographic coordinates 7.4671576° S and 112.7769319° E. The study site was selected based on an official spatial planning directive issued by the local government, which designates the coastal area of Desa Gebang, Tambak Kedungpeluk, Kecamatan Sidoarjo, Kabupaten Sidoarjo, as a zone for integrated aquaculture development. This location was chosen as it represents a typical coastal pond environment in the eastern region of Sidoarjo. The testing was conducted by targeting key water quality parameters, namely pH, total dissolved solids (TDS), and water temperature, which are considered critical indicators of aquatic environments. The results of the water quality observations are presented in Table 1-Table 7, based on daily measurements conducted from 08:00 to 18:00 local time over the observation period.

The results of the seven-day test show that the developed sensor system, which includes the pH4502C sensor for measuring pH, the DS18B20 digital sensor for measuring temperature, and the TDS Meter v1.0 module for measuring total dissolved solids (TDS) during all observation periods The pH levels were between 7.15 and 8.39, the temperature levels were between 21°C and 27°C, and the TDS levels were between 167.51 ppm and 277.51 ppm.The system's average errors were 1.87% for pH measurement, 5.69% for temperature, and 5.09% for TDS. This was based on a comparison of the sensor readings and the calibrator values.

Table 1. Day One Test Result

No.	Time (WIB)	Sensor			Calibrator			Error		
		pH	Temp. (°C)	TDS	pH	Temp. (°C)	TDS (PPM)	pH (%)	Temp. (%)	TDS (%)
1	08.00	8.14	26	181.12	8.1	24.5	180	0.49	6.12	0.62
2	09.00	8.16	26	181.12	8.1	25.0	179	0.74	4.00	1.18
3	10.00	8.12	25	184.54	8.2	25.6	181	0.98	2.34	1.96
4	11.00	8.12	25	170.66	8.2	26.1	180	0.98	4.21	5.18
5	12.00	8.16	25	172.40	8.2	27.0	182	0.49	7.41	5.27
6	13.00	8.16	25	172.40	8.2	27.3	183	0.49	8.42	5.78
7	14.00	8.33	23	168.24	8.2	26.8	181	1.59	14.18	7.06
8	15.00	8.32	23	175.53	8.2	26.0	180	1.46	11.54	2.48
9	16.00	8.34	22	180.91	8.1	25.2	179	2.96	12.70	1.07
10	17.00	8.33	22	180.91	8.1	24.8	178	2.84	11.29	1.63
11	18.00	8.33	23	180.98	8.1	24.2	179	2.84	4.96	1.11
Average error sensor (%)								1.36	7.29	3.49

Table 2. Day Two Test Result

No.	Time (WIB)	Sensor			Calibrator			Error		
		pH	Temp. (°C)	TDS	pH	Temp. (°C)	TDS (PPM)	pH (%)	Temp. (%)	TDS (%)
1	08.00	8.11	26	167.51	8.0	25.2	175	1.38	3.17	4.28
2	09.00	8.11	26	179.42	8.0	25.8	186	1.38	0.78	3.54
3	10.00	8.12	25	170.66	8.0	25.6	178	1.50	2.34	4.12
4	11.00	8.16	25	172.40	8.0	26.3	183	2.00	4.94	5.79
5	12.00	8.20	25	168.91	8.1	27.1	182	1.23	7.75	7.18
6	13.00	8.21	25	181.08	8.1	27.5	190	1.36	9.09	4.69
7	14.00	8.26	25	179.35	8.1	27.8	192	1.98	10.07	6.59
8	15.00	8.33	23	168.24	8.2	25.0	176	1.59	8.00	4.41
9	16.00	8.34	22	180.91	8.2	24.0	191	1.71	8.33	5.29
10	17.00	8.39	22	179.06	8.3	23.5	185	1.08	6.38	3.22
11	18.00	8.31	23	173.72	8.2	23.2	183	1.34	0.86	5.06
Average error sensor (%)								1.51	5.70	4.83

Table 3. Day Three Test Result

No.	Time (WIB)	Sensor			Calibrator			Error		
		pH	Temp. (°C)	TDS	pH	Temp. (°C)	TDS (PPM)	pH (%)	Temp. (%)	TDS (%)
1	08.00	8.11	26	167.51	8.0	25.3	176	1.38	2.77	4.83
2	09.00	8.14	26	179.42	8.0	25.7	188	1.75	1.17	4.56
3	10.00	8.12	25	170.66	8.0	26.0	180	1.50	3.85	5.19
4	11.00	8.16	26	172.40	8.0	27.1	183	2.00	4.06	5.78
5	12.00	8.20	27	168.91	8.1	27.8	182	1.23	2.88	7.14
6	13.00	8.21	27	181.08	8.1	27.9	191	1.36	3.23	5.20
7	14.00	8.26	27	179.35	8.1	27.6	194	1.98	2.17	7.57
8	15.00	8.33	25	168.24	8.2	25.9	177	1.59	3.47	4.96
9	16.00	8.34	24	180.91	8.2	24.8	193	1.71	3.23	6.28
10	17.00	8.39	23	179.06	8.3	23.9	186	1.08	3.77	3.73
11	18.00	8.31	23	173.72	8.2	23.3	184	1.34	1.29	5.59
Average error sensor (%)								1.54	2.99	5.62

Table 4. Day Four Test Result

No.	Time (WIB)	Sensor			Calibrator			Error		
		pH	Temp. (°C)	TDS	pH	Temp. (°C)	TDS (PPM)	pH (%)	Temp. (%)	TDS (%)
1	08.00	8.08	25	193.15	8.4	24.6	190	3.54	1.49	1.52
2	09.00	8.09	25	187.99	8.0	26.7	178	1.61	6.40	5.50
3	10.00	8.07	25	182.81	8.4	24.9	175	3.50	0.39	4.46
4	11.00	8.04	25	182.81	8.2	26.2	183	1.95	4.43	0.10
5	12.00	8.01	25	196.59	8.1	27.7	184	1.11	9.75	6.86
6	13.00	8.04	26	194.61	8.2	27.1	189	1.95	4.06	2.97
7	14.00	8.03	26	194.61	8.1	27.5	200	0.86	5.45	2.69
8	15.00	8.08	25	187.99	8.3	25.9	180	2.65	3.45	4.44
9	16.00	8.14	23	200.78	8.3	24.8	193	1.93	7.26	3.96
10	17.00	8.11	23	197.20	8.3	24.1	185	2.29	4.78	6.59
11	18.00	8.13	22	195.68	8.3	23.8	203	2.05	7.56	3.60
Average error sensor (%)								2.13	5.55	4.15

Table 5. Day Five Test Result

No.	Time (WIB)	Sensor			Calibrator			Error		
		pH	Temp. (°C)	TDS	pH	Temp. (°C)	TDS (PPM)	pH (%)	Temp. (%)	TDS (%)
1	08.00	8.02	24	207.39	8.1	25.5	198	0.98	5.88	4.74
2	09.00	8.00	24	210.88	8.2	26.0	192	2.44	7.69	9.83
3	10.00	7.98	25	194.87	8.1	26.3	185	1.48	4.94	5.33
4	11.00	7.94	26	197.97	8.3	27.5	190	4.34	5.45	4.20
5	12.00	7.93	26	206.35	8.1	28.3	188	2.10	8.85	8.89
6	13.00	7.91	26	191.25	8.0	27.6	183	1.12	5.80	4.51
7	14.00	7.97	25	208.57	8.2	27.1	194	2.80	7.20	7.53
8	15.00	7.99	24	200.40	8.1	25.7	190	1.36	6.62	5.47
9	16.00	8.02	23	213.28	8.3	25.4	198	3.37	9.45	7.70
10	17.00	8.01	22	203.01	8.1	24.2	187	1.11	9.09	7.89
11	18.00	8.02	22	215.79	8.3	24.5	195	3.37	10.16	10.67
Average error sensor (%)								2.22	7.42	7.07

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Table 6. Day Six Test Result

No.	Time (WIB)	Sensor			Calibrator			Error		
		pH	Temp. (°C)	TDS	pH	Temp. (°C)	TDS (PPM)	pH (%)	Temp. (%)	TDS (%)
1	08.00	7.39	22	253.79	7.5	23.5	238	1.47	6.38	6.66
2	09.00	7.48	22	241.16	7.6	24.1	222	1.58	8.73	8.63
3	10.00	7.44	22	246.58	7.5	24.7	232	0.80	6.93	6.31
4	11.00	7.43	22	253.79	7.7	25.6	239	3.51	8.74	6.22
5	12.00	7.41	22	257.40	7.6	26.2	231	2.50	9.65	10.26
6	13.00	7.46	23	241.65	7.6	26.8	227	1.84	7.09	6.49
7	14.00	7.39	23	255.77	7.5	27.3	240	1.47	8.98	6.16
8	15.00	7.42	23	255.77	7.6	27.1	237	2.37	7.70	7.93
9	16.00	7.50	22	259.20	7.8	26.3	244	3.85	8.57	6.24
10	17.00	7.45	22	262.80	7.6	25.4	238	1.97	7.46	9.45
11	18.00	7.43	22	262.80	7.6	24.6	245	2.24	6.96	7.28
Average error sensor (%)								2.23	7.93	7.33

Table 7. Day Seven Test Result

No.	Time (WIB)	Sensor			Calibrator			Error		
		pH	Temp. (°C)	TDS	pH	Temp. (°C)	TDS (PPM)	pH (%)	Temp. (%)	TDS (%)
1	08.00	7.15	26	244.64	7.3	25.5	252	2.05	1.96	2.92
2	09.00	7.26	25	264.58	7.0	25.7	273	3.70	2.72	3.08
3	10.00	7.18	25	264.58	7.1	25.6	270	1.12	2.34	2.01
4	11.00	7.26	23	273.42	7.4	23.8	283	1.89	3.36	3.38
5	12.00	7.29	22	266.41	7.5	22.7	275	2.88	3.09	3.13
6	13.00	7.26	22	275.42	7.4	21.5	285	1.89	2.33	3.36
7	14.00	7.26	22	262.80	7.4	22.5	271	1.89	2.27	3.02
8	15.00	7.33	21	262.78	7.5	21.7	270	2.32	3.33	2.68
9	16.00	7.28	21	277.51	7.4	21.8	286	1.64	3.67	2.96
10	17.00	7.36	21	262.78	7.5	21.9	272	1.87	4.11	3.39
11	18.00	7.25	21	270.14	7.4	21.7	284	2.03	3.33	4.88
Average error sensor (%)								2.12	2.95	3.16

Table 8. Summary of seven-day water quality measurements

Parameter	Min	Max	Mean	Std Dev	Mean Error	Accuracy
pH	7.15	8.39	7.94	±0.38	1.87%	98.13%
Temperature (°C)	21.0	27.0	24.0	±1.84	5.69%	94.31%
TDS (ppm)	167.5	277.5	212.9	±35.3	5.09%	94.91%

Table 8 summarizes the seven-day observation results across all parameters. pH ranged from 7.15 to 8.39, with a mean of 7.94 and a standard deviation of ±0.38. Temperature ranged from 21°C to 27°C, averaging 24.0°C (±1.84 °C). The TDS levels ranged from 167.51 ppm to 277.51 ppm, with a mean of 212.9 ppm and a standard deviation of ±35.3 ppm. Compared with the Lutron WA-2017SD reference meter, the average errors were 1.87% for pH, 5.69% for temperature, and 5.09% for TDS, corresponding to accuracy rates of 98.13%, 94.31%, and 94.91%, respectively. Table 9 shows daily error variations: pH measurement remained consistently accurate across all days (error range: 1.36%–2.23%), while temperature and TDS errors fluctuated more, particularly on days 5 and 6, when environmental conditions were less stable.

3.2. Web-Based Monitoring Interface

The user interface was designed using the Flutter framework and directly integrated with the Firebase Realtime Database. This integration results in a responsive and cross-platform web application capable of presenting sensor data in real time. The interface allows end users, particularly aquaculture operators, to remotely observe and assess water quality conditions via mobile or desktop devices. At the application layer, the system continuously fetches sensor data from the cloud using a rolling-window visualization approach. To maintain readability and system performance during frequent data updates, the interface displays the most recent ten data entries, ensuring an effective and user-friendly monitoring experience, as illustrated in Figure 6.

To further assess the system's performance and user experience, the web application's responsiveness was evaluated through backend analysis. Specifically, performance profiling tools available in Visual Studio Code were employed to measure rendering efficiency. The recorded load time was 4771 milliseconds, representing the total duration required for the application to fully render the interface and become interactive, as illustrated in Figure 7. This evaluation confirms the application's operational readiness in practical aquaculture scenarios where responsiveness is critical.

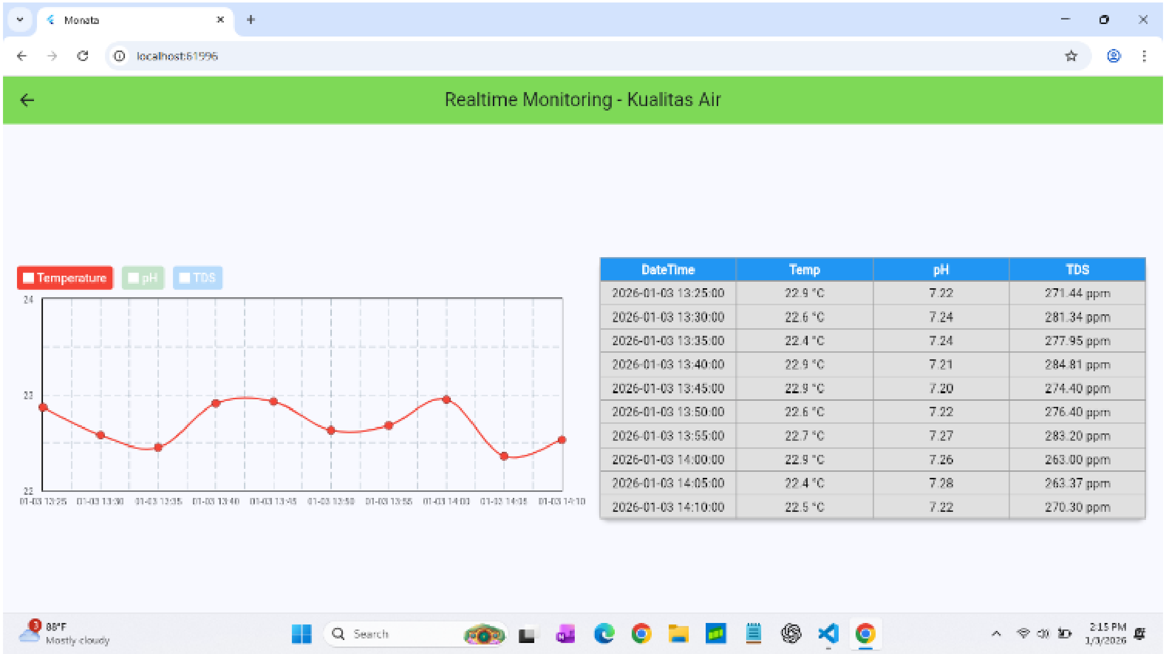

Figure 6. Realtime Data Input

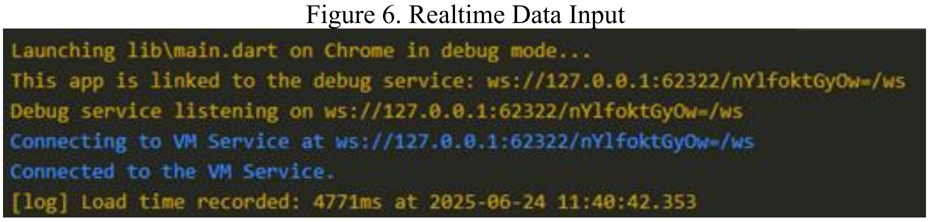

Figure 7. Web Application Performance Profiling

4. CONCLUSION

This research successfully developed a real-time water quality monitoring system by integrating three essential sensors, namely the pH 4502C, DS18B20 temperature, and TDS sensors, into a unified hardware and software prototype based on the Arduino Uno R4 WiFi microcontroller. The system could acquire, process, and transmit environmental data both locally via an LCD display and remotely using a dual communication mechanism involving WLAN and GSM with the LDW931 module. This hybrid communication approach improved data transmission reliability, particularly under unstable network conditions. In addition, implementing a user interface built with the Flutter framework allowed seamless access to real-time data across multiple platforms. This supported remote monitoring for aquaculture practitioners and aligned with the goal of providing a scalable Internet of Things solution for environmental data acquisition.

Field testing in an operational aquaculture pond demonstrated the system's stability and accuracy, confirming its readiness for broader deployment. Overall, the prototype demonstrates initial feasibility under controlled test conditions. The hybrid communication architecture successfully maintained data continuity during simulated network failures. However, broader deployment would require longer-term validation (minimum 30 days), solar power integration, and assessment of sensor fouling. The system's modular design provides a foundation for these extensions, with the failover logic and cloud interface being directly transferable to other environmental monitoring applications.

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