

Implementation and Performance Evaluation of an IoT-Based Multi-Sensor Water Quality Monitoring System for Nile Tilapia Ponds Using an ESP32 Microcontroller

Saharuddin^{1*}, Hasanah Nur², Amiruddin³, Purnamawati⁴

^{1,2,3,4} Graduate School, Universitas Negeri Makassar, Makassar, Indonesia

ABSTRACT: Water quality strongly governs the growth, health, and survival of Nile tilapia (*Oreochromis niloticus*), yet many small- and medium-scale ponds are still monitored manually through periodic sampling, which is labor-intensive, infrequent, and prone to error. This study designed, implemented, and evaluated an Internet of Things (IoT)-based monitoring system that integrates seven sensors with a single ESP32 microcontroller: five water quality sensors (pH, total dissolved solids [TDS], dissolved oxygen [DO], turbidity, and temperature) and two environmental sensors (rainfall and light intensity). Following a research and development (R&D) approach with a waterfall model, the prototype transmitted data to a web-based IoT platform and displayed readings on a local OLED screen. The system was evaluated through component voltage measurements, a 7-day monitoring trial with pond water (May 4–10, 2026), a functionality test by two expert validators, and a usability test with 10 respondents. All sensors and the microcontroller operated as intended, with measured component voltages of 3.7–4.9 V. Over the trial, mean values were 26.48 °C for temperature, 7.31 for pH, 1,060.67 ppm for TDS, 3.41 mg/L for DO, and 39.68 NTU for turbidity; the persistently low DO indicated a need for supplementary aeration. The overall usability score was 83.08%, classified as “very feasible.” The results show that a low-cost, single-board multi-sensor system can provide continuous, remotely accessible records of pond conditions to support decision-making in sustainable tilapia aquaculture. Validation against calibrated reference instruments under field conditions is the recommended next step.

KEYWORDS: Internet of Things; water quality monitoring; ESP32; multi-sensor system; Nile tilapia; aquaculture; real-time monitoring

1. INTRODUCTION

Aquaculture has become one of the fastest-growing food production sectors in the world, and freshwater species such as Nile tilapia (*Oreochromis niloticus*) occupy a strategic position because of their rapid growth, environmental adaptability, and stable market demand. In Indonesia, the world’s second-largest aquaculture producer after China (Food and Agriculture Organization of the United Nations, 2024), tilapia is a major freshwater commodity. Beyond the domestic market, tilapia is internationally recognized as a major contributor to global aquaculture output, which places increasing pressure on producers to intensify production while maintaining environmental sustainability and product quality (El-Sayed & Fitzsimmons, 2023).

Water quality is a key determinant of growth performance, health, and survival in intensive tilapia culture (Mendrofa & Zebua, 2025). Maintaining stable dissolved oxygen (DO) and pH levels is essential for productivity in intensive ponds, whereas environmental stressors such as temperature fluctuations and poor water exchange significantly affect tilapia growth performance (Abd El-Hack et al., 2022). Water quality management should therefore be treated not as a secondary concern in aquaculture operations but as a determinant of sustainable production.

Despite its importance, water quality in many small- and medium-scale tilapia ponds is still monitored manually, relying on periodic sampling and handheld instruments. This approach is inherently limited by low measurement frequency, delayed feedback, and susceptibility to human error, which increase the risk that deteriorating water conditions go undetected and cause economic losses. The Internet of Things (IoT) has emerged as a promising alternative, enabling continuous, automated, and remotely accessible monitoring through networks of low-cost sensors (Flores-Iwasaki et al., 2025). Integrating IoT technology into pond monitoring has been reported to improve operational efficiency by up to 25%, and recent reviews confirm that IoT-based sensing is increasingly adopted across aquaculture systems worldwide to support real-time decision-making (Flores-Iwasaki et al., 2025).

However, most IoT-based pond monitoring systems reported in the literature integrate only a limited number of parameters,

typically two or three variables such as pH and temperature or pH and DO (Al Attas, 2024; Ramadhan et al., 2020). Other ecologically relevant factors, including turbidity, total dissolved solids (TDS), rainfall, and ambient light, are largely left unaddressed. This partial coverage limits farmers' ability to obtain a comprehensive picture of pond conditions and to relate several environmental drivers to one another.

To address this gap, the present study integrates five water quality sensors (pH, temperature, DO, TDS, and turbidity) and two supporting environmental sensors (rainfall and light intensity) around a single ESP32 microcontroller that serves as the central hub for data acquisition and communication. In addition to broader parameter coverage, the system emphasizes continuous monitoring: readings from every sensor are recorded automatically and sent to a web-based platform, where they are stored as a traceable data history that can be reviewed and verified at any time. Unlike manual spot checks, which capture conditions only at the moment of sampling, this continuous record documents water conditions throughout the monitoring period and thus strengthens the system's value as a decision-support tool.

This study addresses two research questions: (RQ1) how can an IoT-based water quality monitoring system for tilapia ponds be designed using multiple sensors and an ESP32 microcontroller, and (RQ2) how does the system perform in terms of functional feasibility and usability? Its contributions are threefold: (i) the design of a low-cost monitoring system that integrates seven chemical, physical, and environmental sensors on a single ESP32 board; (ii) a 7-day trial with pond water that illustrates the continuous records the system produces; and (iii) an empirical assessment of the system's functionality and usability. The remainder of this paper reviews related work (Section 2), describes the materials and methods (Section 3), presents and discusses the results (Section 4), and concludes with the main findings and directions for future work (Section 5).

2. RELATED WORK

2.1. IoT-Based Monitoring in Aquaculture

The Internet of Things refers to an integrated system of devices, actuators, sensors, communication protocols, and intelligent applications that exchange data autonomously over a network (Anggono et al., 2023). In environmental monitoring, IoT enables automated, real-time observation of physical parameters and has delivered substantial benefits across sectors, including fisheries and aquaculture. In aquaculture specifically, a recent systematic review highlights a growing body of work that deploys networked sensors to track water quality continuously, with data made available through mobile or web interfaces (Flores-Iwasaki et al., 2025). Representative implementations include fully automated pond monitoring platforms that combine several sensing nodes with cloud dashboards (Godugolla et al., 2022), general-purpose smart water quality monitoring systems with IoT integration (Chimezie & Ngang, 2025), and an Ubidots-based system for tilapia ponds focused on remote optimization of water parameters (Efendi et al., 2024). Collectively, these studies establish IoT as a mature and field-tested approach to aquaculture water management, although the number of parameters integrated in a single system remains a key point of difference among implementations.

2.2. The ESP32 Microcontroller as a Central Controller

The ESP32 is a system-on-chip (SoC) with integrated Wi-Fi (IEEE 802.11 b/g/n) and Bluetooth connectivity (Nizam et al., 2022). Its combination of adequate processing power, low energy consumption, and built-in wireless modules has made it a popular gateway for IoT monitoring applications, such as web-based door monitoring (Nizam et al., 2022) and an air-conditioner monitoring platform for a preschool (Sutarji et al., 2024). Compared with other common microcontroller platforms such as the NodeMCU, which has been used for shrimp pond monitoring integrated with Firebase and a Flutter mobile application (Ramadhan et al., 2020), the ESP32 offers a relatively larger number of general-purpose input/output (GPIO) and analog input pins. This is an important consideration when several analog and digital sensors must be accommodated simultaneously, as required by the multi-sensor design in this study.

2.3. Water Quality Parameters: pH, Temperature, and Dissolved Oxygen

The pH level, measured with a glass-electrode probe, reflects the acid-base balance of pond water and is a primary indicator of chemical suitability for fish (Ruslianto et al., 2023). Water temperature, commonly sensed with a DS18B20 digital probe capable of measuring from -55°C to 125°C (Ruslianto et al., 2023), regulates metabolic rate and, indirectly, oxygen solubility. Dissolved oxygen is widely regarded as the single most important parameter for the survival of aquatic organisms because it directly governs respiration and metabolic efficiency. IoT-based DO sensing has been reported to achieve a monitoring accuracy of 92.7% and a precision of 98% in common carp culture, confirming that IoT-integrated DO sensors can provide reliable, continuous, and responsive readings to support pond water quality management (Hayati et al., 2025). Given the sensitivity of DO to temperature

and organic load, measuring it alongside temperature and pH is essential rather than optional in a comprehensive monitoring design.

2.4. Dissolved Solids and Optical Parameters: TDS and Turbidity

Total dissolved solids measure the concentration of dissolved organic and inorganic substances, including calcium, sodium, magnesium, phosphate, and nitrate, in pond water. In IoT-based monitoring, TDS sensing enables timely detection of critical thresholds and can trigger automated responses that help stabilize aquaculture management and improve the efficiency of water treatment (Flores-Iwasaki et al., 2025). Turbidity, typically measured with infrared scattering sensors such as the SEN0189 module and expressed in nephelometric turbidity units (NTU), indicates the concentration of suspended particles. Its ease of integration with microcontrollers such as Arduino and ESP32 has made it a standard component of aquaculture IoT systems capable of detecting changes in water clarity in real time (Flores-Iwasaki et al., 2025). Together, TDS and turbidity provide complementary information on chemical loading and physical clarity that is often omitted from the simpler two- or three-parameter systems reported elsewhere (Al Attas, 2024).

2.5. Environmental and Actuation Components: Rainfall, Light, Relay, Pump, and Power Supply

Beyond direct water quality parameters, environmental sensors are increasingly incorporated into IoT systems to help explain observed fluctuations. A rainfall sensor connected to the microcontroller records rainfall events in real time, which can affect pond dilution and runoff-related parameter shifts (Flores-Iwasaki et al., 2025). A light-dependent resistor (LDR) captures ambient light intensity as an analog signal digitized by the microcontroller's analog-to-digital converter (ADC); its variation follows the diurnal cycle and cloud cover and has been linked to DO fluctuations through photosynthesis and respiration (Ramadhan et al., 2020). On the actuation side, an electromechanical relay, available in normally open (NO) and normally closed (NC) configurations, acts as a magnetically operated switch for controlling an automatic water pump (Ruslianto et al., 2023), while a 12 V mini water pump circulates water past the sensor array to ensure representative readings (Djaksana & Gunawan, 2021). The power supply converts 220 V AC to 9 V DC and maintains a stable voltage across all electronic components.

2.6. Research Gap and Positioning of This Study

Overall, the reviewed literature shows that IoT-based water quality monitoring for aquaculture is an established research direction, with individual studies demonstrating strong performance for specific sensing tasks, for example, high DO measurement accuracy (Hayati et al., 2025), effective TDS-triggered automation (Flores-Iwasaki et al., 2025), and the successful deployment of ESP32-based systems for community fish-farming groups (Saharuddin & Syaifuddin, 2025). Nevertheless, relatively few studies integrate seven or more sensing parameters spanning chemical (pH, DO, TDS), physical (temperature, turbidity), and environmental (rainfall, light) domains on a single, centrally coordinated ESP32 platform. This study addresses that gap by designing, implementing, and evaluating such a multi-sensor system and comparing it with narrower single- or dual-parameter implementations such as that of Al Attas (2024).

3. MATERIALS AND METHODS

3.1. Research Design and Location

This study adopted a research and development (R&D) approach, defined as a method that aims to produce a specific product and to test its effectiveness empirically (Judijanto et al., 2024). The research was conducted at the Laboratory of the Department of Electronics Engineering and Information Technology, Faculty of Engineering, Universitas Negeri Makassar, Indonesia.

3.2. Development Model

The system was developed using a sequential waterfall model comprising six stages (Judijanto et al., 2024): (1) requirements analysis, (2) system design, (3) implementation, (4) integration and testing, (5) deployment, and (6) maintenance.

3.3. Research Procedure

The research procedure is shown in Figure 1. It began with requirements analysis and a literature review to collect relevant references and identify system requirements. The hardware and software architecture of all components was then designed, after which the device was assembled and the microcontroller programmed. The assembled system was tested to verify its basic functions; if the trial failed, the assembly stage was repeated. Once the trial succeeded, the device was validated by two expert lecturers to confirm that the data were correct. The system's response under real water conditions was then analyzed, and the results were evaluated and

used to revise the system.

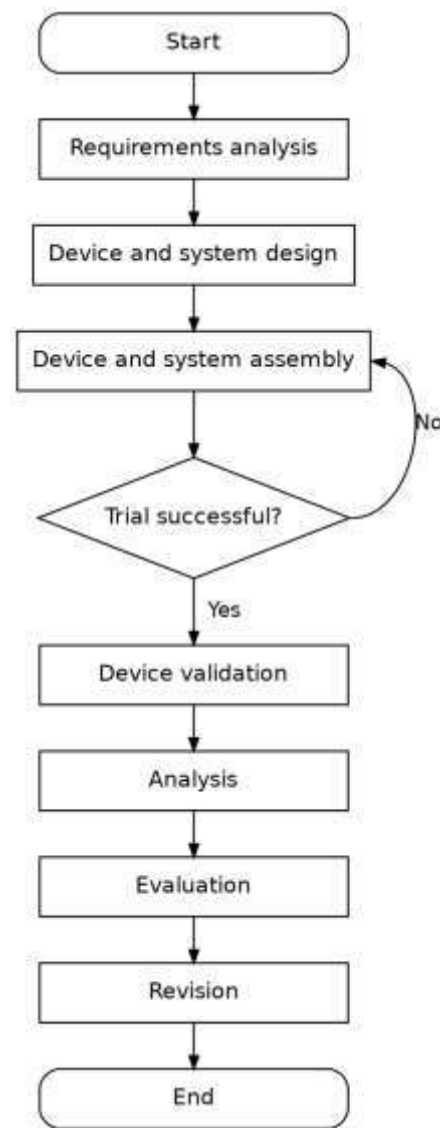


Figure 1. Research procedure.

3.4. Hardware Design

The hardware design (Figure 2) integrates the ESP32 microcontroller as the central controller with five water quality sensors (pH, TDS, DO, turbidity, and temperature), two supporting sensors (rainfall and LDR), a relay module, a water pump, and a power supply. The sensors were mounted on a water-flow pipe within the prototype, whereas the ESP32 and the sensor modules were housed in a panel box together with an OLED display for local readings. Data were transmitted to a web-based IoT platform, where the dashboard was updated every hour, and the local OLED display was updated every minute.

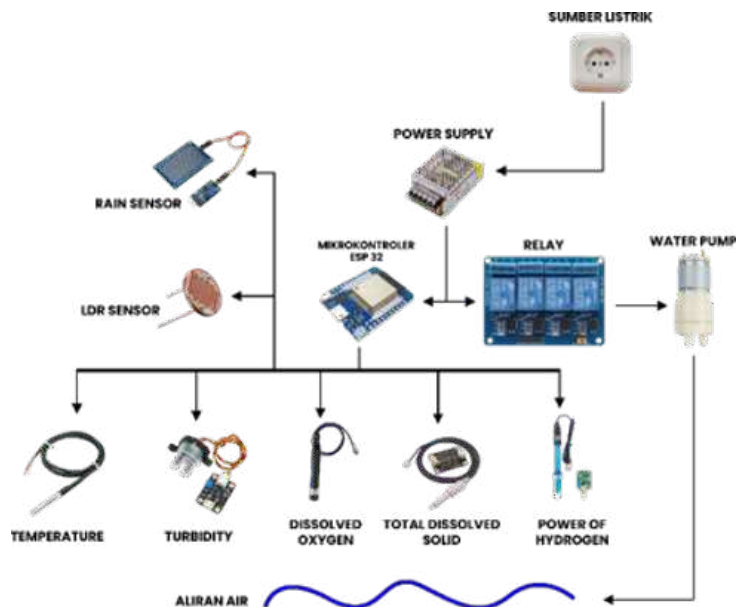


Figure 2. Hardware components of the monitoring system.

3.5. Testing Procedures

The system was evaluated using three complementary methods: (1) laboratory testing, which verified the operating voltages and sensor readings using actual pond water over a 7-day period; (2) functionality testing, in which two expert validators assessed eight test items; and (3) usability testing, in which 10 respondents completed a 13-item Likert-scale questionnaire covering four dimensions: usefulness, ease of use, user satisfaction, and ease of learning. These four dimensions correspond to those of the USE questionnaire (Lund, 2001). Responses were scored on a four-point scale (Table 1).

Table 1. Likert scale scoring.

Response option	Score
Strongly agree (SA)	4
Agree (A)	3
Disagree (D)	2
Strongly disagree (SD)	1

Source: Sugiyono (2012).

The usability percentage was calculated as the ratio of the total score obtained to the maximum possible score:

$$P = (\Sigma \text{ obtained score} / \Sigma \text{ maximum score}) \times 100\%$$

The resulting percentage was interpreted using the feasibility criteria in Table 2.

Table 2. Usability feasibility criteria.

Feasibility percentage	Interpretation
81–100%	Very feasible
61–80%	Feasible
41–60%	Moderately feasible
21–40%	Not feasible
0–20%	Very unfeasible

Source: Adi et al. (2024).

4. RESULTS AND DISCUSSION

4.1. System Realization

The IoT-based monitoring system was successfully realized by integrating seven sensors with an ESP32 microcontroller. The hardware consists of (1) the ESP32 as the central controller that acquires and transmits data; (2) five sensors that measure water quality parameters; (3) two sensors that measure environmental parameters; (4) a relay that controls the automatic pump; (5) a water pump that directs flow across the sensor array; and (6) a power supply that maintains a stable voltage across all components. Data were displayed on the website at hourly intervals and on the local OLED display at 1-min intervals.

4.2. Seven-Day Monitoring Data

Data were collected over seven consecutive days (May 4–10, 2026). Table 3 presents the overall mean values of the water quality and environmental parameters.

Table 3. Overall mean values of the monitored parameters over seven days.

No.	Parameter	Mean value	Interpretation
1	Temperature (°C)	26.48	Stable
2	pH	7.31	Neutral to slightly alkaline
3	TDS (ppm)	1,060.67	Elevated dissolved solids
4	DO (mg/L)	3.41	Low
5	Turbidity (NTU)	39.68	Suspended particles present
6	Rainfall (ADC)	4,093.3	Dry (no rainfall detected)
7	Light intensity (ADC)	2,361.7	Diurnal variation

Temperature remained stable within 25–28 °C, a range suitable for tilapia growth. The pH remained between 7.305 and 7.312, indicating neutral to slightly alkaline conditions. Turbidity decreased progressively from an initial 53.77 NTU on the first day to a 7-day mean of 39.68 NTU, with daily means of approximately 36.4 NTU on later days, a pattern consistent with natural sedimentation or filtration. TDS fluctuated within approximately 1,030.72–1,086.91 ppm on most days, with the lowest value of 1,019.35 ppm recorded on day 7; this reflects a relatively high but consistently monitored dissolved-solids load. DO remained relatively low throughout the trial (mean 3.41 mg/L), below the levels generally recommended for tilapia culture; concentrations under 3.5 mg/L have been reported to reduce growth and feed conversion (Abd El-Hack et al., 2022), which signals a need for supplementary aeration. The rainfall sensor consistently recorded dry conditions during the observation period, whereas the light sensor captured the diurnal day–night cycle.

4.3. Parameter Trends

Figures 3–9 show the time series of each parameter recorded on the web dashboard.

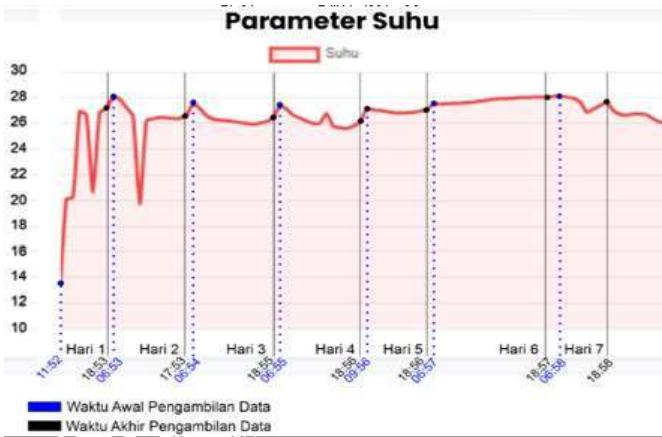


Figure 3. Water temperature over seven days.

Water temperature remained within 25–28 °C throughout the observation period (excluding the initial readings at system start-up on day 1), with an overall mean of 26.48 °C. Values were consistent from the first to the seventh day (Figure 3).

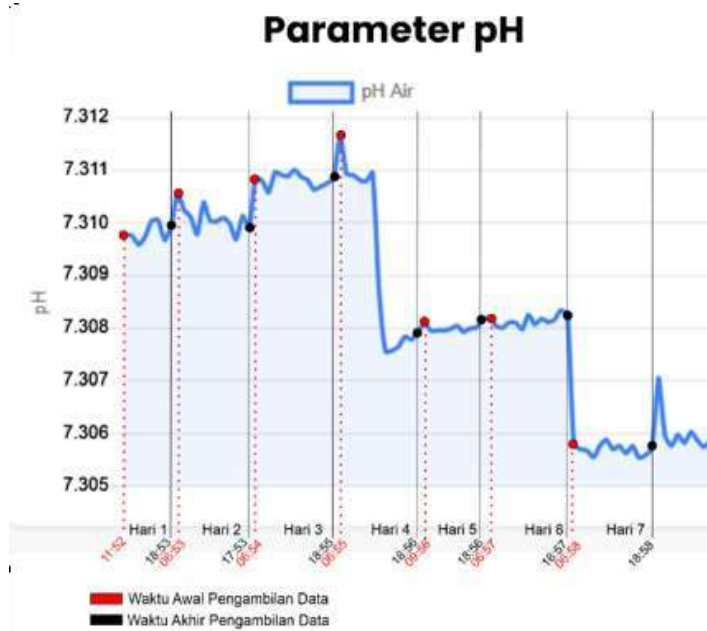


Figure 4. pH over seven days.

The pH ranged from 7.305 to 7.312, with an overall mean of 7.31, within the neutral to slightly alkaline range. Values were consistent throughout the observation period (Figure 4).

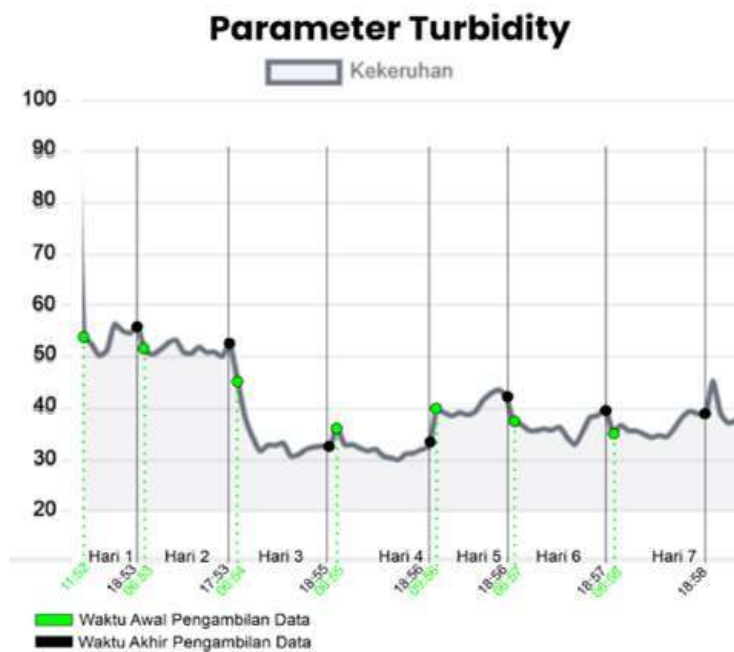


Figure 5. Turbidity over seven days.

Turbidity decreased from 53.77 NTU on day 1 to an overall 7-day mean of 39.68 NTU, with daily means of approximately 36.4 NTU on subsequent days (Figure 5).

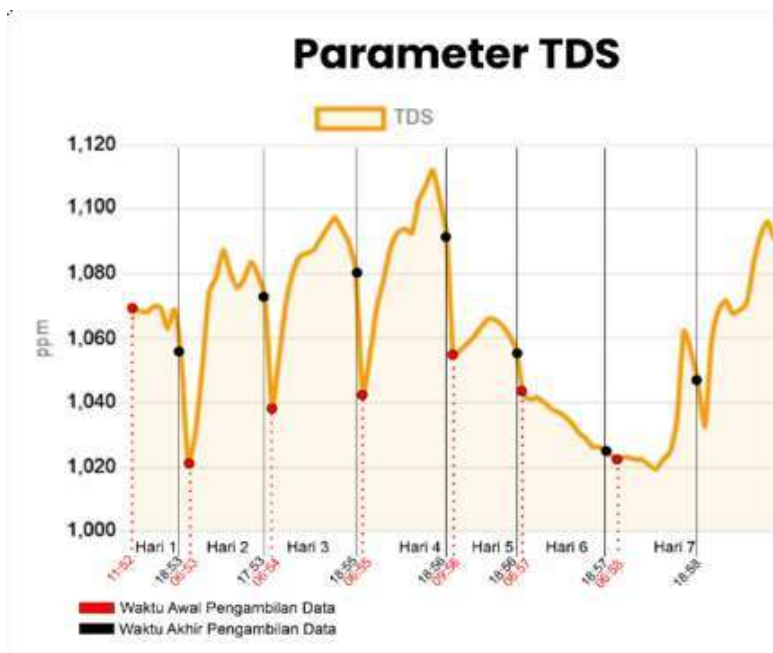


Figure 6. Total dissolved solids (TDS) over seven days.

Daily mean TDS ranged from 1,030.72 to 1,086.91 ppm, with an overall mean of 1,060.67 ppm. The lowest value, 1,019.35 ppm, was recorded on day 7 (Figure 6).



Figure 7. Dissolved oxygen (DO) over seven days.

Daily mean DO ranged from 3.30 to 3.52 mg/L from day 1 to day 6, with an overall mean of 3.41 mg/L. On day 7, the daily mean was 3.38 mg/L, and DO fell below 3.2 mg/L after 18:58 Central Indonesian Time (WITA) (Figure 7).



Figure 8. Rainfall sensor output over seven days.

The rainfall sensor recorded ADC values of 4,092.63–4,093.69 throughout the seven days, with an overall mean of 4,093.3. Because these values lie close to the maximum of the ESP32's 12-bit ADC (4,095), they indicate that the sensor surface remained dry throughout the observation period (Figure 8).

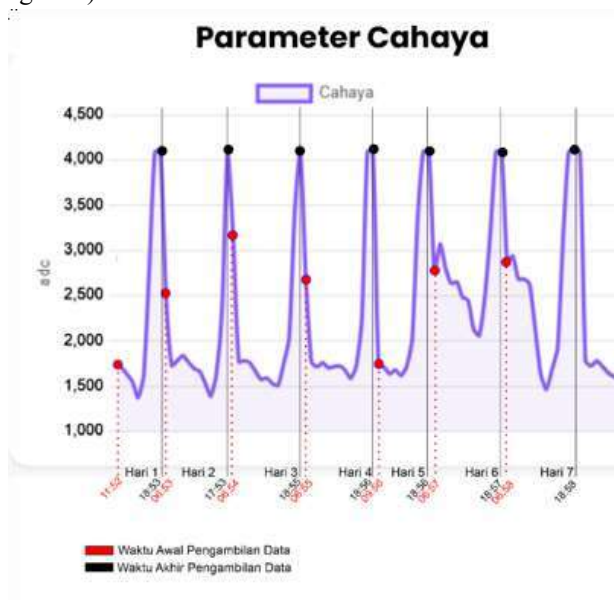


Figure 9. Light intensity over seven days.

Light intensity fluctuated with a daily pattern, with an overall mean of 2,361.7 (ADC). The lowest values were recorded in the afternoon, for example, 1,376 at 14:52 WITA on day 1 and 1,393 at 14:43 WITA on day 2 (Figure 9). In the voltage-divider configuration used, the ADC value decreases as illumination increases; the lowest readings therefore correspond to the brightest periods.

4.4. Functionality Test

Two validators assessed eight test items covering the microcontroller and the seven sensors. Table 4 summarizes the results: all items were rated as functioning.

Table 4. Functionality test results.

No.	Component	Test item	Result
1	ESP32	Can it control the inputs/outputs of the monitoring system?	Yes
2	pH sensor	Can the sensor read the acidity of the water accurately?	Yes
3	TDS sensor	Can the sensor measure dissolved solids in the water?	Yes
4	Temperature sensor	Can the sensor measure water temperature correctly?	Yes
5	DO sensor	Can the sensor read dissolved oxygen levels accurately?	Yes
6	Turbidity sensor	Can the sensor detect the turbidity level of the water?	Yes
7	Rainfall sensor	Can the sensor detect rainfall?	Yes
8	LDR sensor	Can the sensor measure ambient light intensity?	Yes

The validators tested each component directly, judging whether the microcontroller and the seven sensors performed as specified by the test instrument on a yes/no basis.

4.5. Usability Test

Ten respondents completed the 13-item questionnaire. Table 5 reports the total score for each item (maximum 40 per item) and for each dimension; the raw scores of each respondent are provided in Appendix A.

Table 5. Usability test results by item.

No.	Statement	Score	%
Usefulness			
1	The system helps me monitor pond water quality effectively.	35	87.5%
2	The information displayed by the system is very useful for decisionmaking.	34	85.0%
3	The IoT system makes real-time monitoring of water conditions easier.	37	92.5%
4	Multi-sensor integration improves the accuracy of water quality monitoring.	35	87.5%
Ease of use			
5	The system is easy to use without much adjustment.	32	80.0%
6	The information on the display/dashboard is easy to understand.	32	80.0%
7	I have no difficulty using this device.	31	77.5%
User satisfaction			
8	I find this system beneficial for managing tilapia ponds.	35	87.5%
9	I am satisfied with the accuracy of the multi-sensor readings.	32	80.0%
10	I am satisfied with the system's performance in displaying data in real time.	35	87.5%

Ease of learning			
11	The system is easy to learn when using it for the first time.	31	77.5%
12	The operating procedure is easy to remember after instruction.	33	82.5%
13	Users can quickly understand the sensor functions through the system.	30	75.0%

The maximum possible score was 520 (10 respondents $\times$ 13 items $\times$ 4 points), and the obtained score was 432, giving a usability percentage of 83.08%. According to the classification of Adi et al. (2024), this value falls in the “very feasible” category. By dimension, usefulness scored highest (141/160; 88.1%), followed by user satisfaction (102/120; 85.0%), ease of use (95/120; 79.2%), and ease of learning (94/120; 78.3%). Respondents thus judged the system to be useful, informative, and helpful for pond management decisions, while ease of use and ease of learning, both in the “feasible” range, indicate that the dashboard and onboarding could be simplified further.

4.6. Voltage Test and Overall Discussion

Table 6. Component voltage test results.

No.	Component	Supply voltage (V)	Measured voltage (V)
1	ESP32	5.5	4.9
2	Temperature sensor	5.5	3.8
3	pH sensor	5.5	3.9
4	TDS sensor	5.5	3.8
5	DO sensor	5.5	3.9
6	Turbidity sensor	5.5	3.9
7	Rainfall sensor	5.5	3.7
8	LDR sensor	5.5	3.8

Laboratory testing confirmed that the system consistently read data from all sensors. With a 5.5 V supply, the measured voltage exceeded 3.0 V at every component; the differences between components are attributable to the internal resistance and current requirements of each component. The overall performance of the system is consistent with the findings of Saharuddin and Syaifuddin (2025), who demonstrated the effectiveness of IoT-based water quality monitoring for community tilapia-farming groups. Compared with the ESP32-based pond monitoring system reported by Al Attas (2024), this study provides broader parameter coverage by integrating seven sensors simultaneously rather than the narrower parameter sets typical of earlier implementations.

Beyond feasibility, the trial illustrates the practical value of continuous records. The DO level remained low on every day of the trial and declined further in the evening of day 7, a pattern that periodic manual sampling could easily miss. Continuous logging allows such trends to be detected early and linked to supporting variables, such as light intensity, which reflects the diurnal cycle of photosynthesis and respiration.

4.7. Limitations and Future Work

Several limitations should be noted. First, the sensors were not compared with calibrated reference instruments, so the measurement accuracy of each sensor was not quantified; the narrow pH variation observed (0.007 units over seven days) in particular should be verified against a reference meter. Second, the trial lasted seven days at a single site during dry conditions, so the rainfall sensor was not exercised and long-term effects such as sensor drift and biofouling were not assessed. Third, the web dashboard logged data at hourly intervals, which may be too coarse to capture rapid night-time DO declines. Fourth, the usability test involved only 10 respondents (the respondents: farmers and students). Future work should therefore include field validation against reference

instruments over a full production cycle, shorter logging intervals with threshold-based alerts, automatic aeration triggered by DO readings, and an autonomous power supply, such as an off-grid solar panel (Safrudin et al., 2025), for remote ponds.

5. CONCLUSIONS

This study designed and evaluated an IoT-based water quality monitoring system for Nile tilapia ponds built around a single ESP32 microcontroller. First, the system was successfully realized by integrating five water quality sensors (pH, TDS, DO, turbidity, and temperature) and two environmental sensors (rainfall and light intensity), with data acquired automatically and transmitted to a web-based platform. Second, all components functioned as designed, and the system achieved a usability score of 83.08%, in the “very feasible” category. Third, continuous, automated observation improves the speed and continuity of monitoring compared with manual sampling, enabling faster and better-informed decisions to maintain suitable water conditions for sustainable tilapia aquaculture. Validation against reference instruments in field conditions is the main priority for future work.

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Appendix A. Raw Usability Scores

Table A1. Scores given by each respondent (R1–R10) for each questionnaire item.

Item	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Total
1	3	4	4	3	3	3	3	4	4	4	35
2	3	4	4	3	3	3	3	4	3	4	34
3	4	4	3	4	3	4	4	4	4	3	37
4	3	4	4	3	3	3	4	4	3	4	35
5	4	3	3	3	3	3	3	3	4	3	32
6	4	3	3	3	3	3	3	4	3	3	32
7	3	3	3	3	3	3	3	3	4	3	31
8	3	3	4	3	3	4	4	4	4	3	35
9	3	3	4	3	3	3	4	3	3	3	32
10	4	3	3	3	3	3	4	4	4	4	35
11	3	3	3	3	3	3	4	3	3	3	31
12	4	3	4	3	3	3	3	3	4	3	33
13	3	3	3	3	3	3	3	3	3	3	30
Total											432

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