

# Development of a Sensor-Based Telemonitoring System for Temperature, Dissolved Oxygen, pH, and TDS in Floating Net Cage Aquaculture

Humairoh Ratu Ayu<sup>1\*</sup>, Bernitha Putri Liano<sup>1</sup>, Jihan Puspita<sup>1</sup>, Sri Wahyu Suciayati<sup>1</sup>, Hilma Putri Fidyandini<sup>2</sup>, Gurum Ahmad Pauzi<sup>1</sup>, and Amir Supriyanto<sup>1</sup>

1. Department of Physics, Universitas Lampung, Bandar Lampung, 35145, Indonesia.

2. Department of Aquaculture, Universitas Lampung, Bandar Lampung, 35145, Indonesia

## Article Information

### Article history:

Received April 25, 2026

Received in revised form May 22, 2026

Accepted May 23, 2026

**Keywords:** fish farming, water quality, telemonitoring system, sensor, aquaculture

## Abstract

Aquaculture using Floating Net Cage (FNC) systems in Lake Ranau, Lumbok Seminung District, West Lampung Regency, has expanded rapidly, with approximately 600 FNC units currently in operation. However, recurrent upwelling events frequently cause mass fish mortality and deterioration of water quality. Variations in temperature, dissolved oxygen (DO), pH, and total dissolved solids (TDS) significantly influence the overall water quality of the lake. To address these challenges, an Internet of Things (IoT)-based water quality telemonitoring system was developed for aquaculture applications, integrating temperature, DO, pH, and TDS sensors with an ESP32 microcontroller. Water quality data are transmitted in real time to the ThingsBoard platform, enabling continuous remote monitoring. Sensor performance evaluation demonstrated high measurement accuracy, with average accuracies of 98.87% for temperature, 98.37% for DO, 97.59% for pH, and 97.36% for TDS. These results indicate that the proposed telemonitoring system is reliable and effective for supporting water quality management in floating net cage aquaculture systems. Field testing conducted in the FNC system at Lake Ranau showed that the lake water quality was within safe limits, with temperature ranging from 25.32 °C to 29.15 °C, DO from 3.93 ppm to 7.48 ppm, pH values between 6.03 and 7.4, and TDS values below 1000 ppm.

## Informasi Artikel

### Proses artikel:

Diterima 23 April 2026

Diterima dan direvisi dari 20 Mei 2026

Accepted 25 Mei 2026

**Kata kunci:** akuakultur, budidaya ikan, kualitas air, sistem telemonitoring, sensor

## Abstrak

Budidaya perikanan menggunakan sistem Keramba Jaring Apung (KJA) di Danau Ranau, Kecamatan Lumbok Seminung, Kabupaten Lampung Barat, berkembang pesat dengan sekitar 600 unit KJA yang saat ini beroperasi. Namun, peristiwa upwelling yang terjadi secara berulang sering menyebabkan kematian massal ikan dan penurunan kualitas air. Variasi suhu, oksigen terlarut (dissolved oxygen/DO), pH, dan total padatan terlarut (total dissolved solids/TDS) sangat memengaruhi kualitas air danau secara keseluruhan. Untuk mengatasi permasalahan tersebut, dikembangkan sistem telemonitoring kualitas air berbasis Internet of Things (IoT) untuk aplikasi budidaya perikanan, yang mengintegrasikan sensor suhu, DO, pH, dan TDS dengan mikrokontroler ESP32. Data kualitas air dikirim secara real-time ke platform ThingsBoard sehingga memungkinkan pemantauan jarak jauh secara berkelanjutan. Evaluasi kinerja sensor menunjukkan tingkat akurasi pengukuran yang tinggi, dengan rata-rata akurasi sebesar 98,87% untuk suhu, 98,37% untuk DO, 97,59% untuk pH, dan 97,36% untuk TDS. Hasil ini menunjukkan bahwa sistem telemonitoring yang dikembangkan andal dan efektif untuk mendukung pengelolaan kualitas air pada sistem budidaya keramba jaring apung. Pengujian lapangan yang dilakukan pada sistem KJA di Danau Ranau menunjukkan bahwa kualitas air danau masih berada dalam batas aman, dengan suhu berkisar antara 25,32 °C hingga 29,15 °C, DO antara 3,93 ppm hingga 7,48 ppm, nilai pH antara 6,03 hingga 7,4, serta nilai TDS di bawah 1000 ppm.

\* Corresponding author.

E-mail address: rifkidwi@telkomuniversity.ac.id

## 1. Introduction

Fish farming using Floating Net Cage (FNC) systems has expanded rapidly in lake environments, including Lake Ranau, located in Lombok Seminung District, Lampung Regency, Indonesia. Lake Ranau is the second-largest lake in Sumatra, with a total surface area of 12,623 hectares, of which approximately 22% (around 2,700 hectares) is utilized for aquaculture activities. This considerable potential has encouraged the rapid growth of FNC-based aquaculture in Lake Ranau, with approximately 600 FNC units predominantly culturing Nile tilapia (*Oreochromis niloticus*) and common carp (*Cyprinus carpio*) (Fidyandini et al., 2023).

Despite its rapid development, FNC aquaculture in Lake Ranau faces significant challenges, particularly recurrent mass fish mortality events. These events are primarily associated with upwelling phenomena, characterized by vertical mixing of bottom waters, which can result in the sudden death of several tons of fish within a short period (Kanafi, 2023). Upwelling events in Lake Ranau, West Lampung, have repeatedly caused large-scale mortality of Nile tilapia, leading to substantial economic losses for fish farmers and disrupting the continuity of aquaculture operations (Hidayat, 2021). Water quality is a critical factor influencing fish growth and survival, both in cultured and natural aquatic ecosystems. Degraded water quality, resulting from organic and inorganic pollution, can negatively affect fish growth performance, increase susceptibility to disease, and compromise overall fish health (Fauzia & Suseno, 2020). Upwelling events can further exacerbate water pollution by redistributing nutrients and organic matter from bottom sediments into the water column, thereby posing adverse impacts on aquatic organisms, including cultured fish, and degrading the overall aquatic environment (Lihawa & Mahmud, 2017).

Water temperature is a key parameter for the early detection of upwelling events. Colder water possesses a higher density than warmer water; therefore, when surface water becomes denser than deeper layers, it sinks and displaces bottom water upward, generating vertical circulation (Hidayat, 2021). Dissolved oxygen (DO) concentrations are also strongly influenced by water temperature. An increase in temperature of 10 °C can elevate the physiological activity of aquatic organisms by two to three times, thereby increasing respiration rates. However, higher temperatures simultaneously reduce oxygen solubility, potentially resulting in hypoxic conditions (Effendi, 2003).

Water pH is another essential parameter that must be continuously monitored in floating net cage (FNC) systems, as fluctuations in pH significantly affect water quality for Nile tilapia culture. Extreme pH conditions, whether acidic or alkaline, can impair fish growth, induce physiological stress, and ultimately lead to mortality (Fauzia & Suseno, 2020). In addition, total dissolved solids (TDS) play an important role in water quality assessment because they strongly influence aquatic environmental conditions and fish health. Monitoring TDS levels can help fish farmers maintain optimal water quality conditions for Nile tilapia cultivation (Paputungan et al., 2022).

Mass fish mortality in lake-based aquaculture systems often occurs due to delayed information or insufficient monitoring of water quality parameters. In Lake Ranau, water quality measurements in FNC systems are still predominantly conducted manually at monthly intervals. Such conventional monitoring approaches are time-consuming, costly, and inefficient because of the long distance between sampling locations and analytical laboratories (Ramadhawati et al., 2021). Therefore, there is a critical need for a real-time, IoT-based water quality telemonitoring system capable of continuously detecting key water quality parameters.

Several previous studies have investigated water quality monitoring systems for aquaculture, including assessments of environmental carrying capacity and water quality status in floating net cages through pH, DO, transparency, and temperature measurements (Rahayu et al., 2017), pond water quality monitoring systems providing information via Short Message Service (SMS) (Wahyuni et al., 2020), and monitoring systems for marine organism cultivation based on temperature, DO, and salinity displayed on LCD interfaces (Susanto et al., 2020). However, most monitoring systems developed in Indonesia are limited to only two or three key parameters and still rely on manual data acquisition and interpretation.

Despite these advancements, many existing monitoring systems remain limited in terms of sensor integration, real-time data accessibility, or field implementation in floating net cage environments. In addition, studies focusing on multi-parameter telemonitoring systems specifically designed for floating net cage aquaculture are still relatively limited. Therefore, the development of an integrated monitoring system capable of measuring multiple water quality parameters and transmitting the data in real time is essential for improving aquaculture management and reducing the risk of environmental disturbances.

This study aims to develop a sensor-based telemonitoring system for monitoring key water quality parameters—temperature, dissolved oxygen, pH, and total dissolved solids—in floating net cage aquaculture. The system integrates multiple sensors with an ESP32-based microcontroller and a cloud-based data visualization platform to enable real-time monitoring and remote access to water quality information. The proposed system is designed to provide continuous environmental monitoring that can support aquaculture management and early detection of unfavorable water conditions.

## 2. Research Methods

### 2.1 Environmental Requirements of Nile Tilapia

According to Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning Environmental Protection and Management, the national water quality standards for freshwater aquaculture are classified under Class III water bodies. These standards define the permissible ranges for key water quality parameters, including temperature, total dissolved solids (TDS), pH, and dissolved oxygen (DO), as presented in **Table 1**. The acceptable pH range for freshwater aquaculture is 6–9, the maximum allowable TDS concentration is 1000 mg/L, and the minimum dissolved oxygen level is 3 mg/L. For temperature, a deviation of  $\pm 3$  °C from the natural condition of the water body is permitted.

**Table 1.** Lake water quality standard based on Government regulation No. 22 of 2021

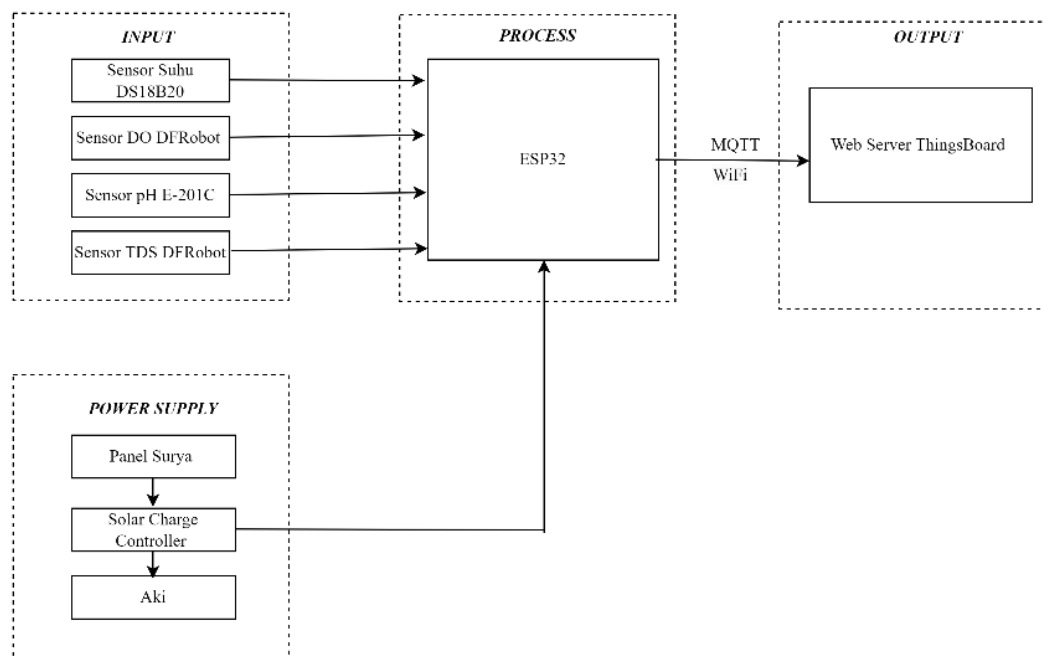
Parameter	Unit	Standard (Class III)
Temperature	°C	Dev. 3
TDS	mg/l	1000
pH	-	6-9
DO	mg/l	Min. 3

In addition to regulatory standards, the optimal temperature range for Nile tilapia (*Oreochromis niloticus*) culture is reported to be between 25 °C and 30 °C (Dailami et al., 2021). Temperature plays a critical role in metabolic activity, feed conversion efficiency, and overall physiological performance. Nile tilapia growth and survival may be significantly impaired when water temperature falls below 14 °C or exceeds 38 °C. Water quality is a fundamental factor in aquaculture systems, as it directly affects fish survival, growth performance, and productivity. The parameters of temperature, pH, DO, and TDS are interrelated and collectively determine the suitability of the aquatic environment. Improper pH levels may induce physiological stress, increase susceptibility to disease, and reduce growth rates and productivity (Nurazizah et al., 2021).

Elevated TDS concentrations are generally associated with feed residues, metabolic waste accumulation, and increased biological activity within the culture system. Excessive TDS levels may disrupt osmotic balance and negatively affect fish health (Nurazizah et al., 2021). Therefore, continuous monitoring and control of water quality parameters are essential to maintain optimal environmental conditions and ensure sustainable Nile tilapia aquaculture practices.

## 2.2 Hardware Design

The hardware architecture developed in this study consists of four primary subsystems: input, processing, output, and power supply. The system is designed to enable real-time telemonitoring of water quality parameters in Nile tilapia aquaculture environments. The input subsystem comprises multiple sensors responsible for acquiring water quality data, including temperature, pH, dissolved oxygen (DO), and total dissolved solids (TDS). These sensors continuously measure the physical and chemical characteristics of the aquatic environment and convert them into electrical signals. The processing unit functions as the core controller of the system, where acquired sensor data are conditioned, digitized, and processed for analysis and transmission. This subsystem manages data acquisition, performs preliminary filtering or calibration if required, and prepares the data for remote communication. The output subsystem provides real-time visualization and data transmission to external monitoring platforms. The processed data can be displayed locally or transmitted wirelessly to a remote server or cloud-based monitoring system for further analysis and storage. The power supply subsystem ensures stable and reliable energy delivery to all components of the system, thereby maintaining continuous operation under field conditions. In general, the overall architecture of the proposed telemonitoring device is illustrated in the block diagram shown in **Figure 1**.



**Figure 1.** Block diagram

**Figure 1** illustrates the hardware block diagram of the proposed telemonitoring system. The hardware architecture consists of a DS18B20 temperature sensor, a DFRobot dissolved oxygen (DO) sensor, an E-201C pH sensor, a DFRobot TDS sensor, an ESP32 microcontroller, a solar panel, a solar charge controller, and a rechargeable battery. In the input stage, the DS18B20 sensor is employed to measure water temperature with digital signal output capability, ensuring stable and noise-resistant data acquisition. The DFRobot DO sensor is used to measure dissolved oxygen concentration in water, which is a critical parameter for fish metabolism and survival. The E-201C pH sensor

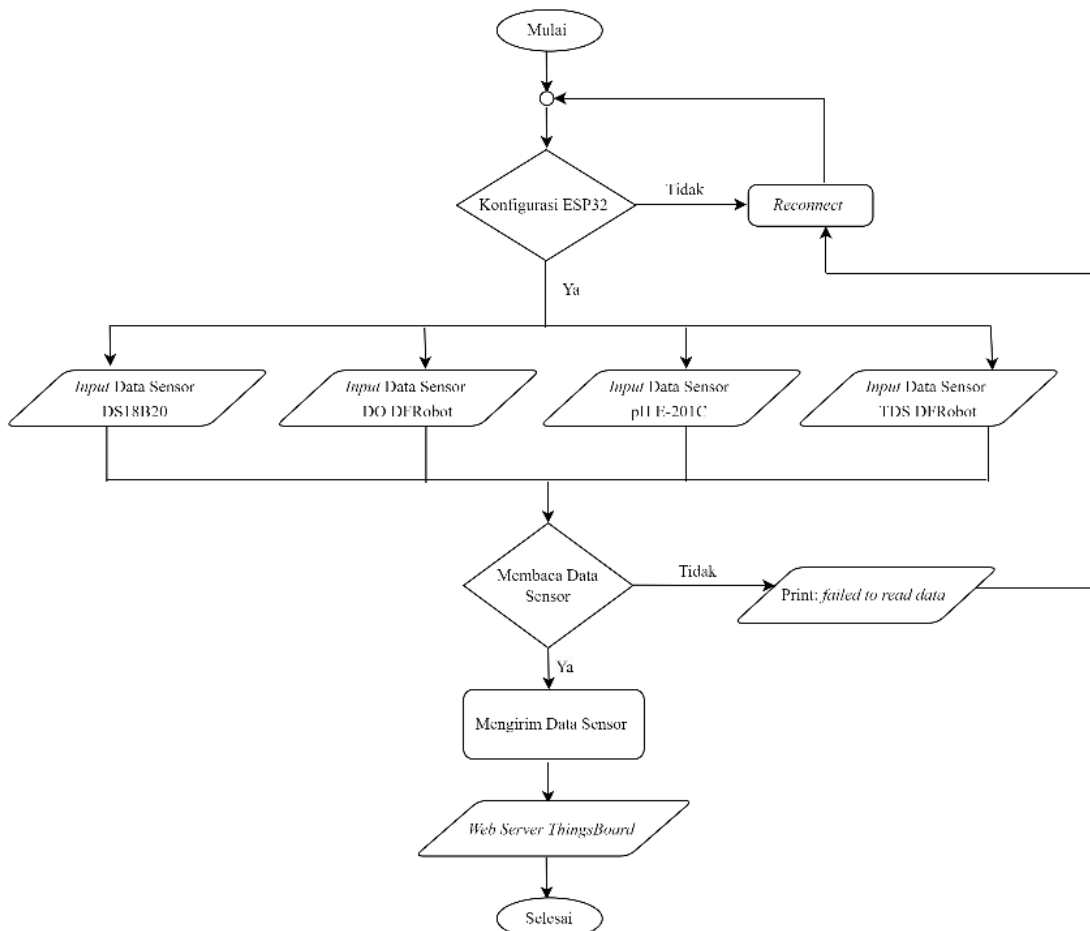
detects the acidity or alkalinity level of the water, while the DFRobot TDS sensor measures the concentration of total dissolved solids in the floating net cage aquaculture system.

The ESP32 serves as the main processing and control unit. It performs sensor data acquisition, signal processing, analog-to-digital conversion (for analog sensors), and communication management. The ESP32 is selected due to its integrated Wi-Fi capability, sufficient processing power, and suitability for Internet of Things (IoT)-based applications. The power supply subsystem consists of a solar panel as the primary energy source, a solar charge controller to regulate voltage and current from the solar panel and prevent overcharging or deep discharge, and a rechargeable battery for energy storage to ensure continuous system operation during low solar irradiance or nighttime conditions.

Data transmission is carried out by the ESP32 via a Wi-Fi network using the Message Queuing Telemetry Transport (MQTT) protocol, which is lightweight and suitable for real-time IoT communication. The transmitted data are forwarded to the ThingsBoard web server platform. The received temperature, DO, pH, and TDS data are stored in the ThingsBoard database and subsequently processed for visualization, monitoring, and further analytical purposes. This integrated architecture enables continuous, real-time, and remotely accessible monitoring of water quality parameters in Nile tilapia aquaculture systems.

### 2.3 Software System Design

The software architecture developed in this study is illustrated in **Figure 2**. The software design governs data acquisition, processing, transmission, storage, and visualization within the proposed telemonitoring system. The software system designed in this study operates sequentially upon initialization. When the system is powered on, it first attempts to establish a Wi-Fi connection by matching the predefined Service Set Identifier (SSID) and password configured in the program code. Once the Wi-Fi connection is successfully established, the ESP32 performs internet connectivity verification to ensure stable network access. After confirming internet availability, the ESP32 initiates the data acquisition process by reading measurements from four sensors: the DS18B20 temperature sensor, the DFRobot dissolved oxygen (DO) sensor, the E-201C pH sensor, and the DFRobot TDS sensor. Each sensor is accessed according to its respective communication protocol (digital or analog), and the acquired data are processed and formatted into structured data packets.



**Figure 2.** Flowchart of Software

The measured data are then transmitted to the ThingsBoard IoT platform via the ESP32 using the MQTT communication protocol. On the platform side, the received data are stored in the database and displayed in real time in the form of numerical values and graphical trends. If the system fails to establish a Wi-Fi connection, data transmission cannot be performed, and consequently, the telemonitoring system will not operate as intended. Therefore, stable network connectivity is a critical requirement for system functionality. Furthermore, the

measurement data obtained from each sensor are used to evaluate system performance in terms of percentage error, accuracy, and precision. The percentage error, accuracy, and precision values are calculated using Equations (1)–(3), respectively.

$$\%Error = \left| \frac{Y_n - X_n}{Y_n} \right| \times 100\% \quad (1)$$

$$\%Accuracy = \left( 1 - \left| \frac{Y_n - X_n}{Y_n} \right| \right) \times 100\% \quad (2)$$

$$\%Presisi = \left( 1 - \left| \frac{X_n - \bar{X}_n}{\bar{X}_n} \right| \right) \times 100\% \quad (3)$$

where  $Y_n$  represents the reference value,  $X_n$  denotes the measured value obtained from the sensor, and  $\bar{X}_n$  indicates the mean of the measured values (Jones et al., 1991).

### 3. Results and Discussions

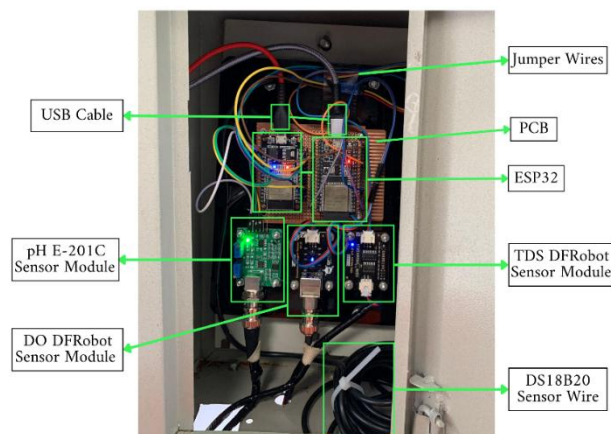
#### 3.1 Sensor Characteristics

Accurate measurement of water quality parameters is essential to ensure the reliability of the telemonitoring system. Therefore, each sensor used in this study was calibrated prior to field deployment. The calibration process was conducted by comparing the sensor readings obtained from the monitoring system with measurements from standard reference instruments. The calibration procedure aimed to determine the accuracy of the sensors and to minimize measurement errors. The hardware testing of the Internet of Things (IoT)-based water quality telemonitoring system was conducted to evaluate both the operational condition of the device and the performance characteristics of the sensors employed. This testing phase aimed to ensure that all hardware components functioned properly and that each sensor was capable of measuring parameter values accurately in accordance with calibration instruments or reference samples. The primary components evaluated in this telemonitoring system included the sensor data acquisition unit and the data transmission module responsible for delivering measurement results via an internet connection to the ThingsBoard platform. Sensor readings obtained from the monitoring device were transmitted in real time and subsequently visualized on the IoT dashboard. The characteristics for temperature, TDS, pH, and DO sensors are shown in **Table 2** and the input and output signals from the DS18B20 temperature sensor, DFRobot dissolved oxygen (DO) sensor, E-201C pH sensor, and DFRobot TDS sensor are processed by the ESP32 microcontroller, as illustrated in **Figure 3**. The ESP32 performs data acquisition and signal processing prior to transmission. The processed data are subsequently transmitted to the ThingsBoard platform for real-time monitoring and further analysis. The ESP32 is powered through a USB interface connected to the Solar Charge Controller (SCC), as shown in **Figure 4**. The SCC regulates the power supplied from the solar energy system to ensure stable operation of the monitoring device.

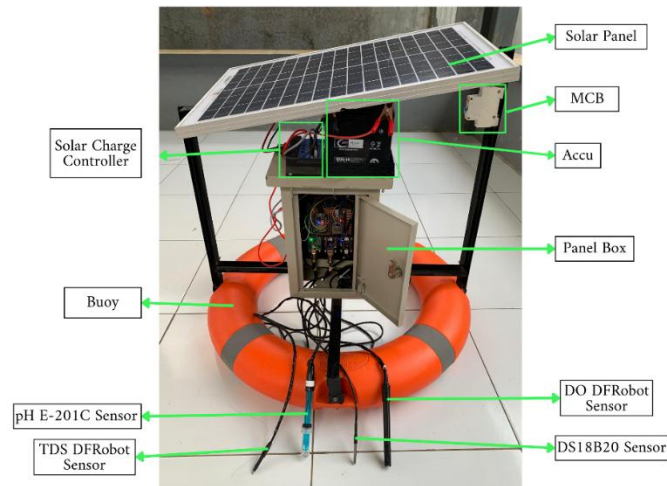
**Table 2.** The characteristic for temperature, pH, TDS, and DO sensors

Sensor	ERROR (%)	Accuracy (%)	Precision (%)
Temperature	1.13	98.87	99.44
TDS	2.64	97.36	99.48
pH	2.41	97.59	99.58
DO	1.63	98.37	98.64

**Table 2** summarizes the validation results for temperature, TDS, pH, and DO sensors after comparing with standard tools. All sensors show the best performance with error under 3%. This indicates that the sensors provide accurate and reliable measurements, making it suitable for use in the water quality monitoring system.



**Figure 3.** Hardware configuration of the assembled IoT-based water quality monitoring system

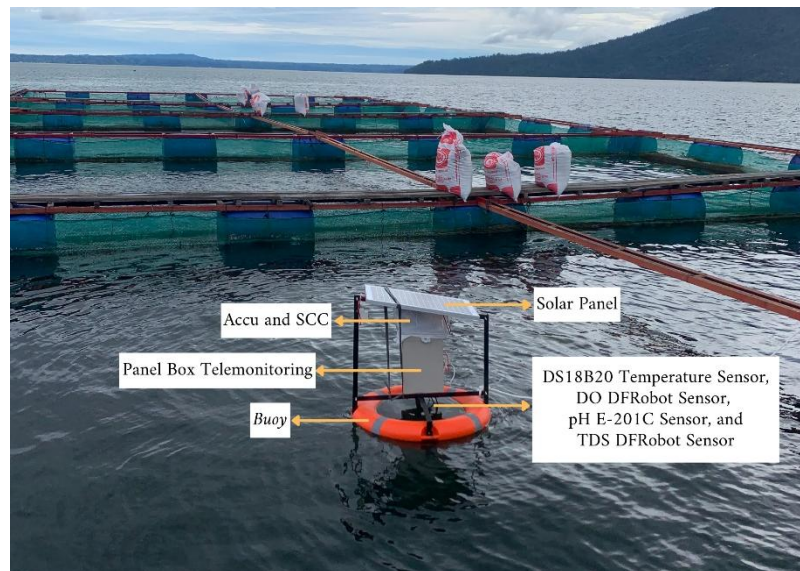


**Figure 4.** External configuration of the IoT-based water quality monitoring system

As shown in **Figure 4**, the ESP32 microcontroller is powered by a rechargeable battery that is charged by a solar panel through a Solar Charge Controller (SCC). The solar panel harvests solar energy and converts it into electrical energy, which is subsequently delivered to the SCC. The SCC regulates the charging process of the battery to prevent overcharging and excessive discharge, thereby ensuring stable and reliable energy management. The battery functions as an energy storage unit, supplying electrical power to the monitoring system. During nighttime or periods of low solar irradiance, when the solar panel does not generate sufficient electricity, the battery provides continuous power to maintain system operation. The SCC is equipped with a USB output port that delivers a stable power supply to the ESP32 microcontroller. The monitoring device is mounted on a buoy system, allowing the solar panel, battery, SCC, and enclosure box containing the ESP32 and sensor modules to remain afloat on the water surface. This floating configuration ensures continuous and real-time water quality monitoring in the aquaculture environment.

### 3.2 Acquisition and Telemonitoring System Analysis

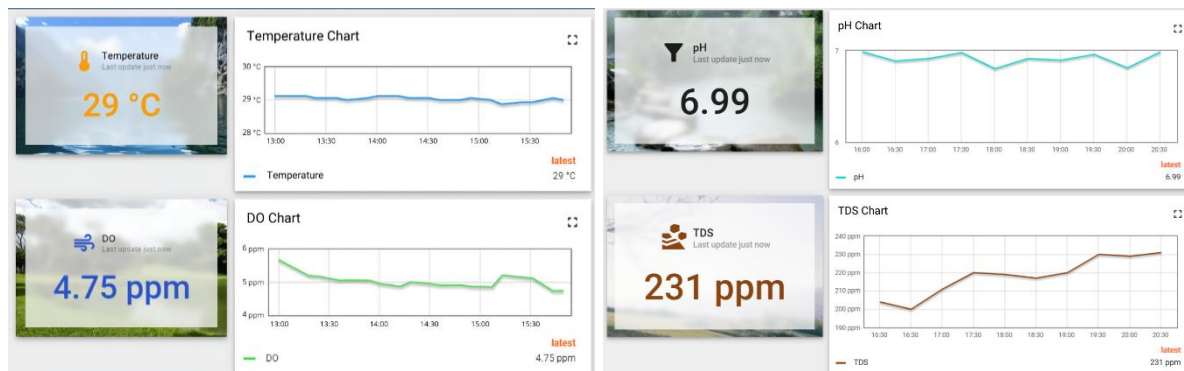
Data acquisition was conducted by implementing the fully integrated telemonitoring system in a Nile tilapia floating net cage aquaculture site. The system was deployed under real environmental conditions to evaluate its operational performance, data transmission reliability, and monitoring capability. The realized telemonitoring system installed at the aquaculture site is shown in **Figure 5**.



**Figure 5.** Overall implementation of the telemonitoring system

The data acquisition process in this study was conducted at a floating net cage aquaculture site in Lake Ranau, Lumbok Seminung District, West Lampung Regency. Field measurements were performed during four observation periods morning, afternoon, evening, and night by monitoring water temperature, dissolved oxygen (DO), acidity level (pH), and total dissolved solids (TDS). Measurements were recorded at 30-minute intervals to capture temporal variations in water quality parameters. The acquired data were transmitted and displayed in real time on the ThingsBoard platform.

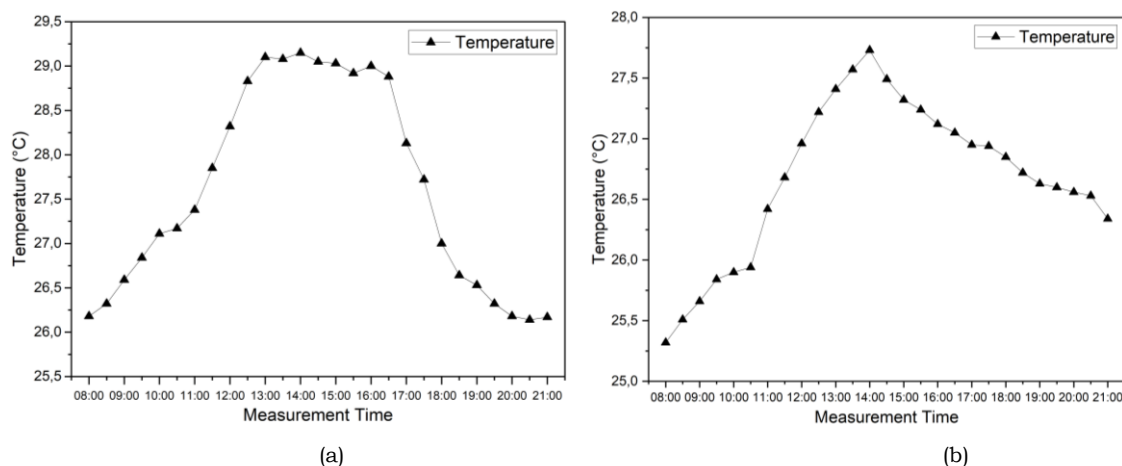
The visualization of temperature, DO, pH, and TDS sensor measurements on the ThingsBoard dashboard is presented in **Figure 6**. This figure presents the dashboard interface of the water quality telemonitoring system, displaying the monitored parameters, namely temperature, dissolved oxygen (DO), pH, and total dissolved solids (TDS). The dashboard layout was intentionally designed with a simple and user-friendly interface to facilitate easy interpretation of sensor readings. The telemonitoring system operates in real time, where parameter updates are continuously reflected on the dashboard. Data transmission from the ESP32 to the ThingsBoard platform remains active as long as the device is connected to a stable Wi-Fi network.



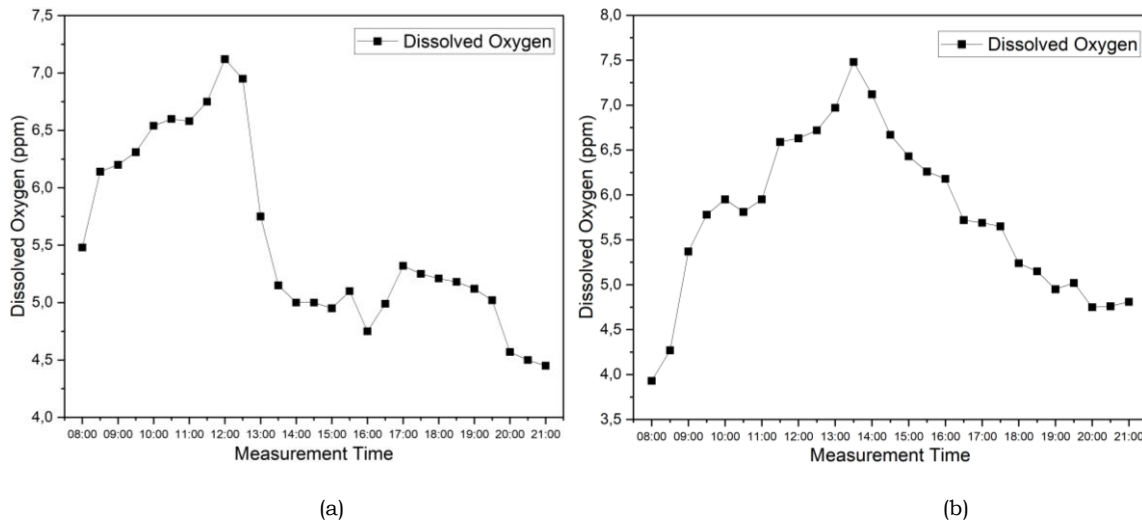
**Figure 6.** Real-time multisensor monitoring results on the ThingsBoard IoT platform

Sensor data transmission is implemented by developing a dedicated ThingsBoard communication program within the Arduino IDE environment, enabling MQTT-based data publishing from the ESP32 to the IoT server. The water temperature measurements at the floating net cage (KJA) in Lake Ranau on the first day are presented in **Figure 7**, while the second-day measurements are shown in **Figure 8**. Observations were conducted from 08:00 to 21:00 WIB at 30-minute intervals. The recorded water temperature exhibited minor fluctuations over the monitoring period. On the first day, the highest temperature was observed at 14:00 WIB, reaching 29.15°C. Similarly, on the second day, the peak temperature occurred at 14:00 WIB, with a value of 27.73°C. The increase in temperature during midday is primarily attributed to solar radiation intensity.

Water temperature variations are influenced by several environmental factors, including seasonal changes, altitude, cloud cover, latitude, solar radiation, water flow, and depth (Effendi, 2003). Based on the two-day monitoring results, the measured temperature values remained within the normal range for Nile tilapia aquaculture. The optimal temperature range for Nile tilapia cultivation is between 25°C and 30°C (Dailami et al., 2021). The overall temperature measurements at the Lake Ranau floating net cage during the two-day observation period ranged from 25.32°C to 29.15°C. These values indicate stable thermal conditions, as no drastic fluctuations were observed. Maintaining temperature within this optimal range is crucial for sustaining normal physiological functions of aquatic organisms and directly influences dissolved oxygen solubility in water (Papatungan et al., 2022).



**Figure 7.** Temperature's measurement (a) The first day, (b) The second day



**Figure 8.** Dissolve Oxygen's measurement (a) The first day, (b) The second day

**Figure 8** presents the dissolved oxygen (DO) measurement results at the floating net cage (KJA) in Lake Ranau over a two-day monitoring period from 08:00 to 21:00 WIB, with measurements recorded at 30-minute intervals. On both the first and second days, DO levels exhibited noticeable fluctuations; however, the values remained within the safe range for Nile tilapia aquaculture. On the first day, the highest DO concentration was recorded at 12:00 WIB, reaching 7.12 ppm. On the second day, the peak DO value was 7.48 ppm at 13:30 WIB. Higher DO concentrations were generally observed during daytime compared to nighttime. This phenomenon is attributed to the balance between respiration and photosynthesis processes. At night, oxygen is consumed by aquatic organisms for respiration, whereas during daylight hours, oxygen is produced by aquatic plants and phytoplankton through photosynthesis driven by solar radiation (Paputungan et al., 2022).

In addition, dissolved oxygen levels may increase due to physical aeration processes such as wave action, waterfalls, wind-induced turbulence, and other natural phenomena that enhance oxygen diffusion into the water column (Panji, 2023). Overall, the two-day DO measurements ranged from 3.93 ppm to 7.48 ppm. Although fluctuations were observed, no abrupt or extreme changes occurred that could endanger aquaculture activities. The recorded DO values remained within the safe range for Nile tilapia cultivation at the Lake Ranau floating net cage site. According to Government Regulation No. 22 of 2021 concerning national water quality standards, the minimum allowable dissolved oxygen concentration for freshwater aquaculture is 3 mg/L. Therefore, the measured DO levels during the monitoring period were considered compliant and suitable for sustainable fish farming operations.

The comparison of water acidity (pH) levels in the floating net cage over the two-day monitoring period is presented in **Figure 9**. On the first day, the water pH remained relatively stable during the morning period (08:00–10:30 WIB), with values ranging from 6.68 to 6.97. During midday (11:00–14:30 WIB), pH values exhibited moderate fluctuations, ranging from 6.29 to 7.12. In the afternoon (15:00–17:30 WIB), pH values varied between 6.35 and 6.98. Similarly, during the nighttime period (18:00–21:00 WIB), pH fluctuations were observed within the range of 6.32 to 6.99.

On the second day, the overall pH values ranged from 6.16 to 6.98, indicating slight fluctuations throughout the monitoring period. Greater variability was observed during midday, with pH values ranging from 6.02 to 7.21. In the afternoon, pH fluctuations were recorded between 6.03 and 7.40, while during the nighttime period, pH values ranged from 6.03 to 7.40. The observed pH fluctuations can be attributed to several environmental and biological factors, including phytoplankton and aquatic plant photosynthesis, light intensity, water transparency, plankton abundance, water temperature, and ammonia concentration (Sandika et al., 2024). The solubility and dynamics of ammonia in aquaculture waters are strongly influenced by feed waste accumulation and pH fluctuations (Lusina Sihombing et al., 2022).

Furthermore, pH levels are closely related to fluctuations in dissolved oxygen ( $O_2$ ) and carbon dioxide ( $CO_2$ ) concentrations associated with photosynthetic and respiratory activities. Increased  $CO_2$  concentration leads to a decrease in pH, whereas higher  $O_2$  levels are generally associated with increased pH values (Santikawati et al., 2023). Based on the two-day monitoring results, the pH levels at the Lake Ranau floating net cage remained within the acceptable range for freshwater aquaculture. According to Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning Environmental Protection and Management, the suitable pH range for freshwater fish cultivation is 6–9. Therefore, the recorded pH values indicate favorable water quality conditions for Nile tilapia farming.

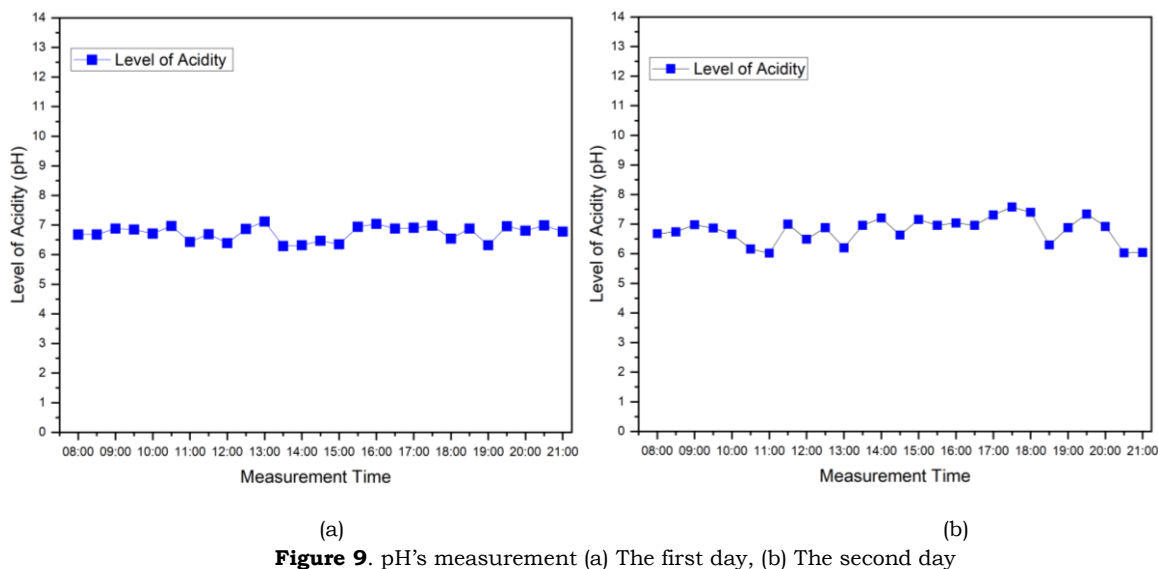


Figure 9. pH's measurement (a) The first day, (b) The second day

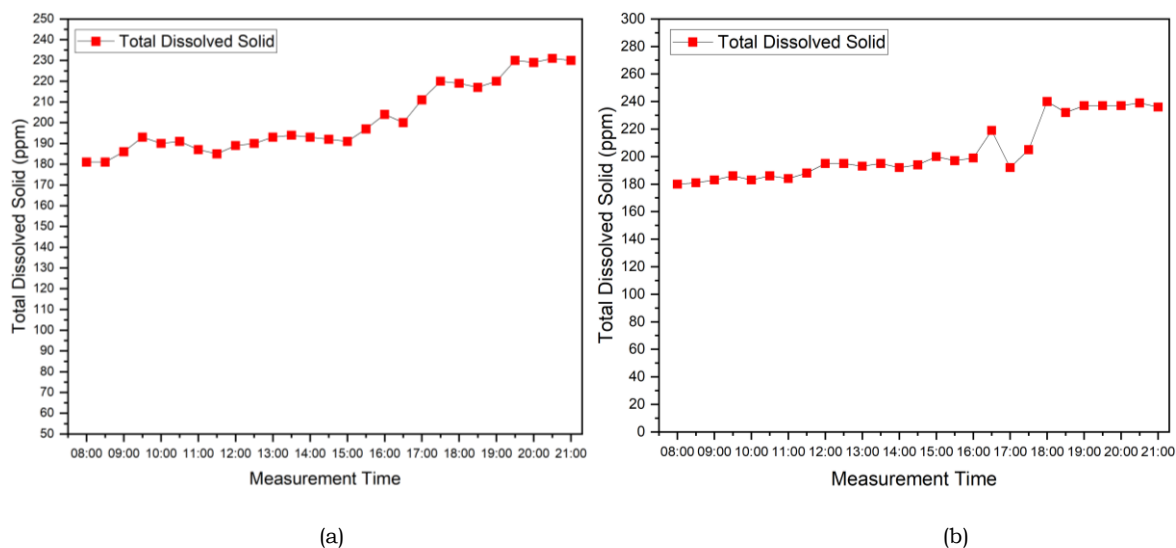


Figure 10. The total dissolved solid's measurement (a) The first day, (b) The second day

On the other side, The comparison of total dissolved solids (TDS) levels in the floating net cage over the two-day monitoring period is presented as follows. On the first day, TDS values during the morning period were relatively stable with minor fluctuations, ranging from 181 ppm to 193 ppm. At midday, TDS values showed slight variations within the range of 185 ppm to 194 ppm. In the afternoon, greater fluctuations were observed, with values ranging from 191 ppm to 220 ppm. During the nighttime period, a more significant increase occurred, with TDS levels ranging from 219 ppm to 231 ppm.

On the second day, morning TDS values remained relatively stable, ranging from 180 ppm to 186 ppm. At midday, larger fluctuations were observed compared to the morning period, with values ranging from 184 ppm to 195 ppm. In the afternoon, TDS variations became more pronounced, ranging from 192 ppm to 219 ppm. During the nighttime period, a significant increase in TDS concentration was recorded, with values ranging from 232 ppm to 240 ppm. The observed fluctuations in TDS levels are primarily influenced by fish activity and growth, dissolved ion concentrations, feed residues, and metabolic waste products (Pratama et al., 2021). Fish movement within the water column may resuspend organic materials deposited at the bottom of the cage system. Dissolved ions originating from soil minerals, rock weathering, and rainwater also contribute to total dissolved solids. In addition, uneaten feed that decomposes in the water increases dissolved solid concentrations, while metabolic waste products released by fish further contribute to TDS accumulation. Based on the two-day monitoring results, the TDS values at the Lake Ranau floating net cage remained within acceptable limits according to Government Regulation of the Republic of Indonesia No. 22 of 2021, which stipulates that total dissolved solids for freshwater aquaculture must not exceed 1000 ppm. Therefore, the recorded TDS levels indicate that water quality conditions were still suitable for Nile tilapia cultivation.

#### 4. Conclusions

An IoT-based multisensor telemonitoring system for water quality assessment in a Nile tilapia floating net cage was successfully designed, implemented, and field-tested. The system integrates temperature, DO, pH, and TDS sensors with an ESP32 microcontroller, MQTT communication protocol, and the ThingsBoard platform for real-time

data acquisition, transmission, and visualization. A solar-powered energy subsystem ensured stable and continuous operation under outdoor conditions. Field evaluation demonstrated reliable sensor performance and stable wireless data transmission at 30-minute intervals. The measured parameters remained within regulatory standards for freshwater aquaculture, confirming both environmental suitability and system measurement consistency. The proposed system demonstrates effective embedded integration, energy autonomy, and real-time monitoring capability, highlighting its potential as a scalable instrumentation platform for smart aquaculture applications.

## Acknowledgements

The authors would like to express their sincere gratitude to the Institute for Research and Community Service (LPPM) of Universitas Lampung for the financial support and facilitation provided through the BLU Grant under the Fundamental research scheme.

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