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Development of a Raw Water Quality Detection System Prior for Municipal Drinking Water Treatment and Sustainable Environmental Management

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Variations in raw water quality can reduce the effectiveness of municipal drinking water treatment processes, making early-stage monitoring prior to treatment essential for sustainable environmental management. This study aims to develop and validate a raw water quality detection system based on an ESP32 microcontroller for real-time measurement of pH, temperature, and turbidity. The research employed an engineering Research and Development (R&D) approach, including system design, sensor calibration, laboratory testing, and field validation. The study was conducted from January to March 2025 in Indramayu Regency, Indonesia, with field testing carried out on river water, seawater, rainwater, and groundwater sources. Measurement accuracy was evaluated by comparing sensor readings with laboratory reference instruments, and accuracy values were calculated based on percentage error and correlation analysis. The results show that the system achieved accuracy levels between 96% and 98%, with correlation coefficients (R^2) greater than 0.9, indicating strong agreement with reference measurements. River water exhibited the highest turbidity value (86.4 NTU), while rainwater showed the lowest pH value (6.3), reflecting distinct environmental characteristics of each water source. Overall, the developed system demonstrated stable performance under real environmental conditions and can function as a low-cost and reliable early detection tool for raw water quality prior to treatment, with potential to support sustainable water resource management.

Keywords: Raw water, pH, Temperature, Turbidity, Sustainable environmental management

INTRODUCTION

Water plays a vital role in human life and the sustainability of ecosystems. The availability of clean water is not only a basic necessity but also a key factor in supporting public health and economic development. According to the *World Health Organization* (WHO, 2023), more than two billion people worldwide still lack access to safe and adequate drinking water. This indicates that water quality remains a global issue that must be addressed with serious attention. The United Nations Environment Programme (UNEP, 2022) emphasizes that efficient and sustainable water resource management is one of the fundamental pillars in achieving the Sustainable Development Goals (SDGs), particularly Goal 6, which aims to ensure the availability of clean water and sanitation for all.

In Indonesia, the demand for clean water is largely supplied by municipal drinking water utilities (Paksi et al., 2021; Sa'adat & Widiyanto, 2024). The quality of treated drinking water is highly dependent on the condition of the

raw water used, which generally originates from rivers, reservoirs, or groundwater sources. However, these water sources are highly dynamic and often affected by weather changes, agricultural activities, as well as domestic and industrial waste (Kementerian PUPR, 2021). Fluctuations in raw water quality can reduce the efficiency of the water treatment process and increase the operational and maintenance costs of treatment units.

Several physical and chemical parameters are commonly used as indicators of raw water quality, including turbidity, acidity level (pH), and temperature. Turbidity represents the concentration of suspended particles that may interfere with coagulation, filtration, and disinfection processes, while pH and temperature influence chemical reactions and microbial activity during water treatment (APHA, 2017; Sutisna et al., 2020). Therefore, continuous and reliable monitoring of these parameters is therefore essential as an early-stage evaluation mechanism prior to treatment, enabling more

effective operational decision-making at municipal water treatment facilities.

Various studies have developed water quality monitoring systems using sensor-based and microcontroller-based platforms. For instance, (Rahmad et al., 2019) developed an Arduino-based system to measure pH and temperature, but the system did not include turbidity monitoring. Other studies implemented Internet of Things (IoT)-based monitoring to transmit water quality data remotely; however, many of these systems were tested only under laboratory conditions and were not optimized for fluctuating environmental characteristics commonly encountered at municipal raw water source (Kurniawan et al., 2022; Sari et al., 2024). In addition, a number of low-cost monitoring systems rely on microcontrollers with limited processing capability and analog-to-digital converter (ADC) resolution, which may reduce measurement stability and accuracy in real-time field environments.

Fitriyanto et al., (2022) introduced a turbidity sensor based on a light-emitting diode (LED) and photodiode configuration, demonstrating that this approach is effective for detecting turbidity changes with relatively low cost and good sensitivity. However, the study focused primarily on sensor development and did not evaluate system integration or field performance in diverse natural water sources. On the other hand, (Khoerun et al., 2023) developed a multiparameter water quality measurement device capable of measuring temperature, pH, total dissolved solids (TDS), salinity, and turbidity. Although the system provided comprehensive parameter coverage, its evaluation was limited to controlled environments, and its role as an early-stage raw water detection tool under real field conditions was not explicitly addressed. The other hand, (Suhanto, 2025) in her literature review "Kajian Penggunaan Sensor dalam Sistem Pengujian dan Pemantauan Kualitas Air Minum Layak Konsumsi" on the application of sensors for drinking water quality testing highlights the growing use of sensor-based systems integrated with microcontrollers and IoT technologies to monitor physical and chemical water parameters in real time. This review suggests that such systems can provide accessible and accurate water quality data, but also notes the need for further advancements in data processing and predictive capabilities to improve reliability and practical utility for safe water supply applications

Based on these previous studies, it can be observed that most existing research emphasizes either sensor development or laboratory-scale system validation, while limited attention has been given to early-stage raw water quality monitoring through direct field testing on multiple natural water sources. Moreover, few studies have critically discussed the limitations of commonly used microcontroller platforms in terms of data processing speed, ADC resolution, and measurement stability for real-time environmental monitoring.

To address these gaps, this study aims to develop and validate an ESP32-based raw water quality detection system capable of providing accurate and stable

measurements of turbidity, pH, and temperature as an early detection tool for municipal raw water quality. The ESP32 microcontroller is selected as a methodological advantage due to its higher processing speed, higher ADC resolution, and improved measurement stability compared to conventional Arduino-based platforms (Hercog et al., 2023; Barral Vales et al., 2022) .

The developed system integrates three main sensors: a turbidity sensor based on an LED-photodiode configuration, an electrochemical pH sensor, and a digital temperature sensor (DS18B20). Each sensor underwent calibration using standard reference methods to improve measurement accuracy. Subsequently, the system was tested on various natural water sources, including river water, seawater, rainwater, and well water, to evaluate its performance under real environmental conditions.

Based on these considerations, this study aims to develop and validate an ESP32-based raw water quality detection system capable of providing accurate and stable measurements of turbidity, pH, and temperature as an early detection tool for municipal raw water quality prior to treatment. The proposed system is expected to offer a practical, low-cost, and reliable solution to support sustainable water resource management and improve the efficiency of water treatment processes in Indonesia.

METHOD

Research Design

This study is classified as engineering research employing a Research and Development (R&D) approach aimed at designing, constructing, and evaluating a raw water quality detection system capable of monitoring turbidity, pH, and temperature parameters in real time to support environmental management and improve the efficiency of municipal drinking water treatment processes. The R&D approach was selected to produce an applied technological product through systematic and iterative stages, including needs analysis, system design, prototype development, calibration and laboratory testing, field testing, and performance evaluation (Sugiyono, 2019).

The research process began with a needs analysis stage to identify critical water quality parameters required for assessing raw water feasibility prior to treatment, based on relevant national regulations and technical guidelines (Kemenkes, 2021; PUPR, 2021). This analysis identified turbidity, pH, and temperature as key indicators of raw water quality. Based on these findings, the system design stage was carried out by integrating the selected sensors into an ESP32 microcontroller module. The designed system was then implemented through prototype development and functional testing to ensure proper operation. The overall research process and methodological flow are illustrated in the research flowchart shown in Figure 1.

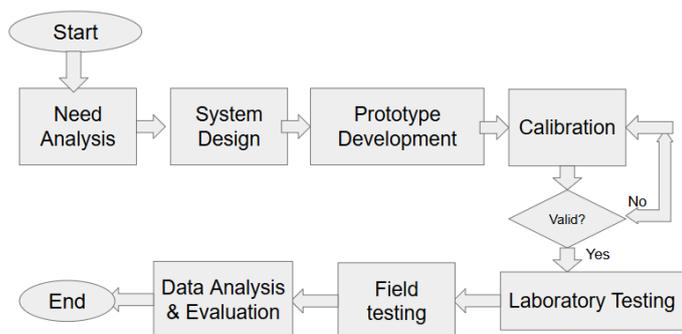


Figure 1. Research Flowchart

Measured Parameters

The developed system was designed to measure three water quality parameters: turbidity, pH, and temperature. These parameters were selected based on municipal raw water quality requirements and their direct influence on water treatment efficiency. Although the printed circuit board (PCB) layout provides an additional slot for a Total Dissolved Solids (TDS) sensor (Steininger et al., 2023), this sensor was not activated or included in the measurement process. Therefore, TDS was not considered as a measured parameter in this study and is reserved solely for future system development. All analyses and results presented in this research are strictly limited to turbidity, pH, and temperature measurements to ensure methodological consistency.

Tools and Materials

The tools and materials used in this study are presented in Table 1. The system consists of an ESP32 microcontroller as the main processing unit (El-Khozondar et al., 2024), integrated with a turbidity sensor (TSD-10) (Algiffary & Sutabri, 2023), an electrochemical pH sensor (pH-4502C) (Ali, 2024), and a digital temperature sensor (DS18B20) (Huda & Kurniawan, 2022). Measurement results are displayed in real time using a 16×2 LCD display, and all electronic components are housed in a waterproof acrylic enclosure to ensure safe operation during field testing.

Table 1.
Tools and materials

Component	Spesification	Description
Microcontroller	ESP32	Main processing unit for sensor data acquisition and real-time display.
Turbidity Sensor	TSD-10 (LED-Photodiode Type)	Measures water turbidity based on light scattering from suspended

Component	Spesification	Description
pH Sensor	pH-4502C (Electrochemical)	particles (in NTU). Detects the acidity or alkalinity level of raw water.
Temperature Sensor	DS18B20 (Digital)	Measures the temperature of water samples accurately.
LCD Display	16×2 Character LCD	Displays real-time readings of turbidity, pH, and temperature values.
Power Supply	5 V DC Adapter	Provides electrical power to the ESP32 system and sensors
Laptop / PC	4 GB RAM, Arduino IDE	Used for programming, calibration, and data analysis
Connecting Cables	Male-Female Jumper Wires	Connects microcontroller pins to the sensors and display.
Prototype Box (Casing)	Waterproof Acrylic Enclosure	Protects electronic components from water exposure during field testing.
Test Water Samples	River, sea, rain, and well water	Used for calibration and performance testing under different environmental conditions.

Component	Spesification	Description
Standard Buffer Solutions	pH 4, 7, and 10	Used for calibrating the pH senso
Kaolin Suspension	0–500 NTU Standard	Used for calibrating the turbidity sensor.
Digital Thermometer (Reference)	Laboratory-grade	Serves as a reference for validating temperature sensor accuracy.

Calibration Procedure

Sensor calibration was conducted prior to laboratory and field testing to ensure measurement accuracy. Each calibration point was measured five times, and the average value was used for analysis. The pH sensor was calibrated using standard buffer solutions with pH values of 4, 7, and 10. The turbidity sensor was calibrated using clear water (0 NTU) and kaolin suspensions with turbidity levels ranging from 0 to 500 NTU. The temperature sensor (DS18B20) was validated using a laboratory-grade digital thermometer as a reference.

The calibration procedure followed the Standard Methods for the Examination of Water and Wastewater (APHA, 2017) and referred to previous studies by (Fitriyanto et al., 2022) and (Khoerun et al., 2023). Measurement error was calculated as a percentage relative to the reference instrument using Equation (1):

$$Error(\%) = \frac{|X_{sensor} - X_{reference}|}{X_{reference}} \times 100 \quad (1)$$

The error values presented in Table 2 represent average percentage error (%). An error value below 5% was considered acceptable for environmental water quality monitoring applications.

Laboratory Testing

After calibration, laboratory testing was conducted to evaluate sensor functionality, data stability, and system linearity. Each parameter was tested using controlled water samples, and measurements were recorded for 10 minutes with a sampling interval of one second. This procedure resulted in 600 data points for each test condition. The laboratory tests ensured that the system produced stable and consistent readings prior to field deployment.

Field Test Design

Field testing was conducted to evaluate system performance under real environmental conditions. Water samples were collected from four different natural water

sources: (1) Cimanuk river water; (2) Karangsong seawater; (3) rainwall collected during rainfall events; and (4) Groundwater from wells in Lohbener Village, Indramayu, Jawa Barat. Sampling was carried out during daytime hours between 09.00 and 11.00 WIB under dry weather conditions, except for rainwater sampling, which was conducted during rainfall. River and seawater samples were collected at approximately 30 cm below the water surface to minimize surface disturbances, while groundwater samples were taken after flushing the well for five minutes to obtain representative samples. Each field test was conducted for 10 minutes with a one-second measurement interval, resulting in 600 replicated measurements per water source.

Data Analysis and Evaluation

The collected data were analyzed by calculating average values and percentage error relative to laboratory reference instruments. System performance was evaluated based on measurement accuracy, stability, and correlation with reference devices. The results of this evaluation were used to assess the feasibility of the developed system as an early detection tool for municipal raw water quality monitoring and to formulate recommendations for future system development.

RESULT AND DISCUSSION

System Implementation

The developed system integrates turbidity, pH, and temperature sensors into a single ESP32-based module designed for early-stage raw water quality monitoring prior to municipal drinking water treatment processes. The system is designed to provide real-time measurements displayed directly on a 16x2 LCD, enabling rapid assessment of raw water conditions relevant to environmental health and water safety.

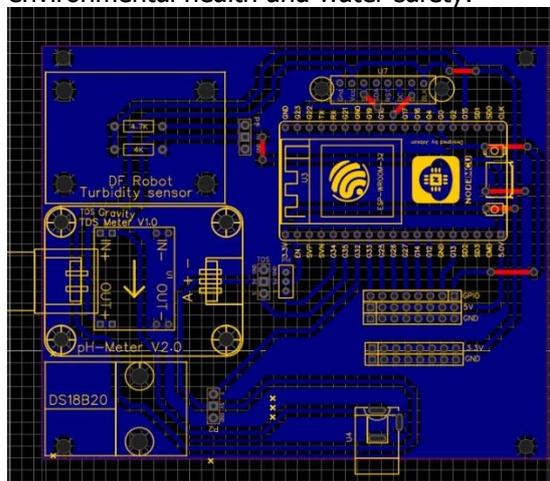


Figure 1. PCB Layout

Although the Printed Circuit Board (PCB) integrates multiple sensors in a compact configuration (Figures 1 and 2), the emphasis of this study is not on electronic design complexity but on system functionality and applicability for environmental monitoring. The ESP32 microcontroller serves as the central processing unit for simultaneous

multiparameter acquisition and real-time data processing. This configuration enables stable measurements under diverse environmental conditions typically encountered at municipal raw water intake locations.

Overall, the system implementation prioritizes practicality, portability, and measurement reliability rather than advanced hardware complexity, making it suitable for deployment as an early detection tool in environmental health monitoring contexts.

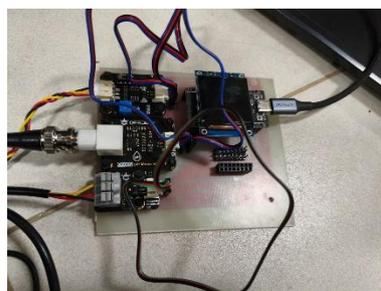


Figure 2. The Result PCB

Sensor Calibration Results

Before the field testing was conducted, each sensor was calibrated using reference standards to ensure measurement accuracy. The calibration process was carried out based on the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2017).

Table 2.

Sensor Calibration Results

Sensor Type	Calibration Standard	Reference Method	Average Error
pH Sensor	Buffer solutions at pH 4, 7, and 10	APHA 4500-H ⁺	2.1
Turbidity Sensor	Kaolin suspension (0–500 NTU)	APHA 2130B	3.4
Temperature Sensor (DS18B20)	Digital laboratory thermometer	APHA 2550B	1.8

The calibration results showed that all sensors had a relative error rate of less than 5%. This value remains within the tolerance limit of standard environmental laboratory measurements (Fitriyanto et al., 2022; Khoerun et al., 2023), indicating that the system is ready for field testing. The calibration process and results are presented in Figure 3.

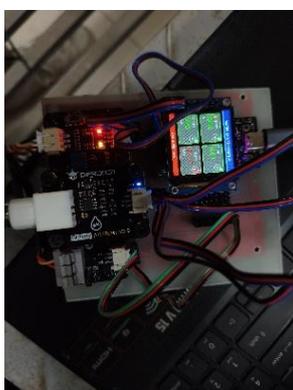


Figure 3. Sensor Calibration

Field Test Result

Field testing was conducted on four natural water sources commonly used as municipal raw water supplies, including river water, seawater, rainwater, and groundwater. Each test was carried out for 10 minutes with a one-second sampling interval, resulting in 600 data points per parameter. The results are presented as mean \pm standard deviation. The average measurement results for each parameter are presented in Table 3.

Table 3.

Sensor Calibration Results

Water Source	pH	Temperature (°C)	Turbidity (NTU)	General Characteristic
River Water	6.8	29.5	86.4	Turbid after rainfall; slightly acidic condition due to suspended sediments.

Water Source	pH	Temperature (°C)	Turbidity (NTU)	General Characteristic
Sea Water	8.2	30.1	45.6	Stable readings; high salinity with alkaline pH caused by dissolved salts.
Rainwater	6.3	27.8	22.5	Clear appearance; slightly acidic due to atmospheric CO ₂ absorption.
Well Water	7.1	28.3	35.2	Clear and stable; near-neutral pH conditions suitable for municipal raw water abstraction and treatment.

River water exhibited the highest turbidity levels, exceeding recommended municipal raw water quality thresholds, whereas groundwater demonstrated the most stable and suitable characteristics for intake.

Data Analysis

Data variability analysis indicates that river water and rainwater tend to have lower pH values associated with higher turbidity levels. To examine this relationship, a linear regression analysis was performed between average turbidity and pH values obtained during field testing. The analysis resulted in a coefficient of determination (R^2) of 0.81, indicating a strong negative correlation between turbidity and pH.

This correlation suggests that increased suspended solids influence chemical equilibria in water, leading to a decrease in pH. The regression analysis was conducted using averaged field data, and the relationship is illustrated in Figure 4 (scatter plot of pH versus turbidity). These findings are consistent with previous studies reporting interactions between suspended solids and water acidity (Sutisna et al., 2020).

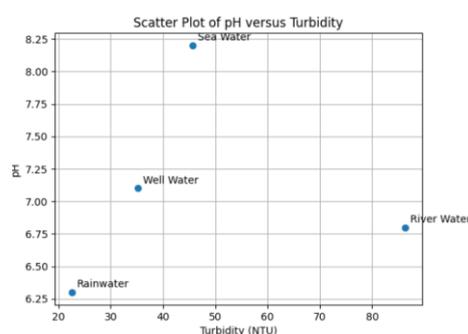


Figure 4. Scatter Plot of pH Vs Turbidity

Figure 4. shows a scatter plot of pH versus turbidity obtained from field test data. The results indicate a negative correlation trend, where higher turbidity values are associated with lower pH levels. Linear regression analysis yielded a coefficient of determination (R^2) of 0.81, indicating a strong relationship between turbidity and pH in natural raw water samples.

System Performance Evaluation

System performance was evaluated by comparing ESP32 sensor readings with laboratory reference instruments, including a benchtop pH meter, a laboratory turbidimeter, and a calibrated digital thermometer. Accuracy was calculated using the percentage accuracy formula:

$$Accuracy(\%) = \left(1 - \frac{|X_{sensor} - X_{reference}|}{X_{reference}} \right) \times 100$$

The results of this comparison are presented in Table 4.

Table 4
Comparison of ESP32 Sensor Readings with Laboratory Reference Instruments

Parameter	Average Reading (ESP32 System)	Average Reading (Reference Instrument)	Accuracy (%)	Correlation Coefficient (R^2)
pH	7.10	7.04	97.8	0.96
Temperature	28.3	28.1	98.2	0.98

Parameter	Average Reading (ESP32 System)	Average Reading (Reference Instrument)	Accuracy (%)	Correlation Coefficient (R ²)
Turbidity (NTU)	47.4	46.0	96.1	0.93

The system achieved accuracy values between 96% and 98% with strong correlations ($R^2 > 0.9$), confirming its reliability for environmental water quality monitoring.

The results demonstrate that the developed ESP32-based system is capable of reliably measuring pH, temperature, and turbidity as primary indicators of raw water quality prior to municipal water treatment. The high accuracy values obtained (96–98%) and strong correlations with laboratory reference instruments ($R^2 > 0.9$) indicate that the integration of low-cost sensors with an ESP32 microcontroller can meet the accuracy requirements for environmental water quality monitoring. This finding supports previous studies reporting that appropriately calibrated low-cost sensors can provide performance comparable to laboratory instruments for field applications (Fitriyanto et al., 2022; Khoerun et al., 2023).

Variations observed among different water sources reflect their distinct environmental characteristics. River water exhibited the highest turbidity levels, likely due to surface runoff and suspended sediments, which may increase treatment complexity and chemical consumption during the coagulation and filtration processes. In contrast, groundwater showed more stable pH and turbidity values, indicating lower exposure to surface contamination and greater suitability as a raw water source for municipal abstraction. Rainwater presented low turbidity but slightly acidic pH values, which can be attributed to atmospheric CO₂ dissolution, while seawater showed alkaline pH associated with high dissolved mineral content. These findings are consistent with established water quality characteristics reported in environmental monitoring studies (Sutisna et al., 2020; Alim et al., 2021; WHO, 2023).

The negative correlation observed between turbidity and pH ($R^2 = 0.81$) highlights the interaction between suspended particles and water chemistry in natural water bodies. Increased suspended solids may influence buffering capacity and chemical equilibria, leading to pH reduction. The ability of the system to capture this relationship using field data demonstrates its effectiveness in identifying meaningful environmental patterns, rather than merely producing numerical readings.

Compared with Arduino-based platforms commonly used in earlier studies, the ESP32 microcontroller provided improved processing speed and measurement stability, contributing to lower error rates and more reliable continuous monitoring (Rahmad et al., 2019; Kurniawan et al., 2022; Sarkar & Hossain, 2021). This methodological advantage is particularly important for early-stage raw

water monitoring, where rapid and stable measurements are required to support operational decision-making at water treatment facilities (UNEP, 2022; Chatterjee et al., 2024).

Despite its promising performance, this study has several limitations. The system operates as a standalone device without real-time data transmission, and field testing was conducted over a limited time period and number of sampling locations. In addition, only three water quality parameters were evaluated. Future studies may address these limitations by extending long-term monitoring, incorporating additional parameters, and integrating wireless data transmission for real-time decision support.

CONCLUSIONS

This study successfully developed and validated an ESP32-based raw water quality detection system capable of measuring pH, temperature, and turbidity as key indicators of raw water quality prior to municipal water treatment. The system demonstrated reliable performance, with accuracy values ranging from 96% to 98% and strong correlations with laboratory reference instruments ($R^2 > 0.9$), confirming its suitability for early-stage raw water quality assessment.

Field testing across river water, seawater, rainwater, and groundwater samples showed that the system can effectively distinguish variations in physical and chemical characteristics under real environmental conditions. These results indicate that the proposed system can serve as a practical and low-cost monitoring tool to support municipal water supply operations before treatment processes are applied.

Although the current system functions as a standalone monitoring device, its ESP32-based architecture offers potential for future integration with networked or IoT-based monitoring systems. Overall, this study contributes to the development of accessible and reliable water quality monitoring technologies and supports sustainable water resource management efforts aligned with Sustainable Development Goal 6 on clean water and sanitation.

SUGGESTIONS

The developed system still offers opportunities for further improvement and extension. Future work is recommended to integrate the system with Internet of Things (IoT) technology to enable remote and real-time monitoring of raw water quality through wireless communication. This integration would enable continuous

monitoring of multiple municipal raw water sources and improve responsiveness to rapid water quality changes.

Additional enhancements may include the incorporation of other water quality parameters, such as Total Dissolved Solids (TDS), Dissolved Oxygen (DO), and Electrical Conductivity (EC), to provide a more comprehensive assessment of physical and chemical water characteristics. Periodic sensor calibration in accordance with the *Standard Methods for the Examination of Water and Wastewater* is essential to ensure long-term reliability. Further field validation across a wider range of municipal raw water sources, including rivers, reservoirs, and groundwater wells, is recommended to evaluate system performance under diverse and prolonged environmental conditions. These improvements would strengthen the system's applicability as a practical tool for supporting sustainable raw water quality monitoring and management.

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