Smart Digital Measurement System for Rural Water Quality Monitoring Using IoT

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Abstract— Clean water is essential for public health and quality of life. Yet, many rural areas in Indonesia still rely on well water that often has high turbidity, too many dissolved solids, and risks of biological contamination. To help solve these problems, this study created and tested a Smart Digital Measurement System using Internet of Things (IoT) technology to monitor and improve water quality. The system includes a digital monitoring unit with pH, TDS, and turbidity sensors, which send data to the Blynk IoT dashboard and a Telegram bot for notifications. It also uses a multi-stage filtration unit with sedimentation filters, activated carbon, and UV sterilizers. Tests on wells in Gesikan, Tuban, showed the system worked reliably, with an average data transmission delay of 1.72 seconds, sensor errors below 5%, and 99% uptime over seven days. Water quality improved: pH levels rose to nearly neutral (6.8 to 7.0), TDS dropped by more than half (from 520–560 ppm to 240–260 ppm), and turbidity fell by about 75% (from 30–35 NTU to 6–8 NTU). These results show that the system offers an affordable way to help rural communities get cleaner water and supports progress toward SDGs 3 (Good Health and Well-being) and 6 (Clean Water and Sanitation).

Kata Kunci— sensors, water quality, filtration, Internet of Things, SDGs, rural monitoring

I. INTRODUCTION

Clean water is a basic human need that plays an important role in maintaining health, sanitation, and improving quality of life. However, the availability of clean water in Indonesia still faces major challenges, especially in rural areas. Based on data from the Central Statistics Agency (BPS) in 2024, nationally 92.64% of households have access to proper drinking water, but there are still 7.36% of households that are not protected. The disparity is evident between urban and rural areas: in urban areas, the access rate reaches 96.56%, while in rural areas it is only 87.06%. This means that around 12.94% of rural households still have difficulty obtaining water that meets drinking standards.

In many villages, communities still rely on groundwater sources from dug wells or bore wells that do not undergo adequate treatment processes. This condition causes the water to have high turbidity levels, excessive calcium content, and potential biological contamination such as Escherichia coli bacteria. This problem not only reduces quality of life, but also increases the risk of waterborne diseases such as diarrhea, gastrointestinal infections, and skin diseases. In addition, excessive mineral content also affects household appliances and creates an additional economic burden on the community.

The issue of clean water availability and quality in rural areas is not only a local issue, but also relates to the global agenda. The United Nations (UN), through the Sustainable Development Goals (SDGs) 2030, emphasizes the importance of access to clean water and proper sanitation (SDG 6) as well as improving public health (SDG 3). Therefore, technology-based innovation efforts in clean water management at the rural level have a strategic role in supporting the achievement of these sustainable development targets.

Along with technological developments, digitization in the field of instrumentation and measurement systems has become one of the potential solutions to overcome the limitations of clean water management in rural areas. Digitization enables measurement processes that were previously performed manually and were limited in scope to transform into automated, accurate systems connected to information networks. With this approach, water quality can not only be measured at a given moment, but can be monitored continuously to provide a more comprehensive picture of conditions.

The use of the Internet of Things (IoT) provides opportunities for real-time, remote monitoring of water quality at a relatively low cost compared to conventional systems [1], [2]. Through a wireless connection, measurement data can be sent directly to a cloud-based application or mobile device, allowing the community and village administrators to immediately find out the actual water conditions. This is especially important in rural areas that are far from laboratory services or modern water treatment facilities.

In a technical context, the integration of several key sensors—such as a pH sensor to measure acidity levels [3], a Total Dissolved Solids (TDS) sensor to determine dissolved mineral content, and a turbidity sensor to measure turbidity levels [4], [5]—forms a comprehensive digital measurement system. The combination of data from these various parameters produces more accurate information about water quality than using just one type of sensor.

Various international studies have successfully developed IoT-based water quality monitoring systems with various parameters such as pH, TDS [6], turbidity, and temperature [7], as well as improving accuracy and predictive capabilities, including LSTM and LPWAN-based systems [8], [9], cloud and ARIMA, and even portable spectrometers for specific contaminant detection [10]. However, almost all of them are limited to monitoring and prediction functions, without interventions such as multi-stage filtration, and have not been tested in actual rural conditions.

At the national level, several studies have developed real-time monitoring and water quality prediction systems for PDAM or households using IoT [11], but these have not yet been integrated with active filtration solutions, and their sustainability in rural communities has not been tested. Therefore, this study attempts to address this gap by presenting an IoT-based Smart Digital Measurement System that combines multi-parameter monitoring, multi-stage filtration, and real-world testing in rural areas as a real-time, practical, and sustainable digital solution.

II. Methodology

A. Research Methodology Flow

The research methodology flow can be explained through seven main stages as shown in Figure 1.

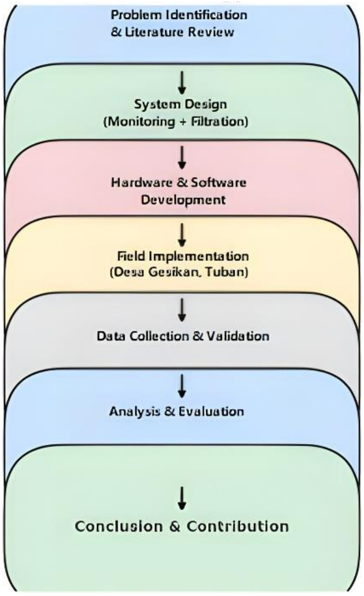


Figure 1. Research Methodology Flow

The first stage is Problem Identification and Literature Review, which is the process of identifying problems related to clean water availability in rural areas while reviewing relevant previous studies. The results of the literature review are used to determine the direction of the research and develop a conceptual framework for the system.

The second stage is System Design, which includes the design of a digital monitoring unit with pH, TDS, and turbidity sensors based on ESP32 and ESP8266 microcontrollers, as well as a multi-stage filtration unit consisting of sedimentation filters, activated carbon, and UV sterilizers. At this stage, the IoT architecture is also determined, which includes the use of MQTT and HTTP API communication protocols, as well as a digital platform for visualization and monitoring.

The third stage is Hardware and Software Development, which involves assembling sensors, developing IoT circuits [3], [12], and creating monitoring applications through Blynk IoT [13] and Telegram Bot. Sensor calibration is performed to ensure that the measurement results are in line with laboratory standards [4], [14].

The fourth stage is Field Implementation, where the designed system is installed and tested directly in the field, specifically in Gesikan Village, Tuban. Field trials are conducted to ensure that the system is capable of functioning in real conditions with rural water characteristics.

The fifth stage is Data Collection and Validation, which is the process of collecting water quality data before and after filtration. The measurement results are compared with manual/laboratory tests to validate the accuracy of the sensors and the reliability of the digital system.

The sixth stage is Analysis and Evaluation, where data is analyzed to assess the effectiveness of the monitoring system and the performance of multi-stage filtration. The analysis is carried out by calculating changes in parameter values (pH, TDS, turbidity) and evaluating whether water quality has improved in accordance with applicable standards.

The final stage is Conclusion and Contribution, which is the preparation of research conclusions and scientific contributions. This research is expected to offer practical and sustainable solutions for the provision of clean water based on instrumentation digitization in rural areas.

B. System Design

This study proposes the development of an IoT-based Smart Digital Measurement System for monitoring water quality in rural areas. The system is designed with consideration given to measurement accuracy, affordability, ease of implementation, and sustainability. In general, the system consists of two main components, namely a Digital Monitoring Unit and a Multi-Stage Filtration Unit.

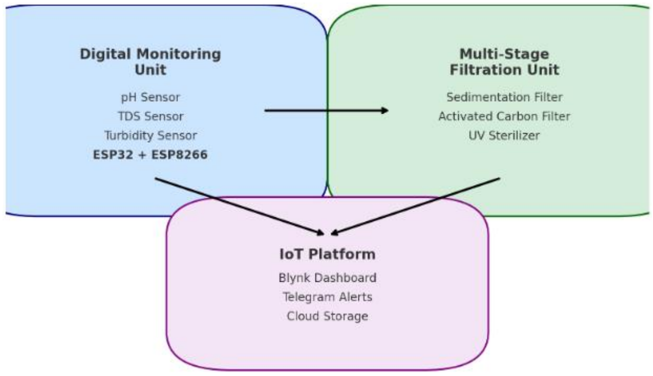


Figure. 2. System Design

1) Digital Monitoring Unit: The monitoring unit is designed to acquire water quality data in real time using a combination of low-cost but reliable sensors [1], [2].

a) Microcontroller: This system uses an ESP32 microcontroller as the main controller—handling the processing of pH and turbidity sensor data—and an ESP8266 as an additional module for reading the TDS sensor, as this sensor requires a voltage stability that is more suitable for this module. Both are configured to communicate with each other and send data to the server/cloud.

b) Sensors used: Three types of sensors were used in this study, namely pH sensors to measure the acidity or alkalinity of water, TDS (Total Dissolved Solids) sensors to detect the amount of dissolved substances [6], and turbidity sensors to measure the level of turbidity [7].

c) Data Processing and Transmission: Data obtained from the three sensors is processed digitally through ADC conversion, then calibrated so that the results comply with laboratory measurement standards. After that, the data is transmitted wirelessly via a Wi-Fi network to the IoT platform (Blynk and Telegram) so that it can be monitored in real-time by users.

2) Multi-Stage Filtration Unit: The filtration unit is designed to improve water quality based on monitoring results. This filtration system works in stages with different types of filter media [5].

a) Sedimentation Filter: Filters out coarse dirt, sand, mud, and large particles. This stage prevents damage to the next filter.

b) Activated Carbon Filter: Absorbs harmful chemicals, odors, and colors in the water. Effectively reduces calcium and organic substances.

c) UV Sterilizer: Uses ultraviolet (UV-C) light to deactivate harmful microorganisms such as bacteria and viruses. This stage complements the filtration system so that the water is not only clear, but also microbiologically safe.

With this design, the system is not only capable of providing real-time water condition data, but also shows the filtration performance in improving water quality. This makes this study different from previous studies, which generally only focus on monitoring without integrating water quality improvement solutions.

C. IoT Architecture and Digital Platform

The IoT architecture in this system is designed so that water quality measurement data can be monitored in real time, either through a dedicated application or instant messaging applications that are easily accessible to the public.

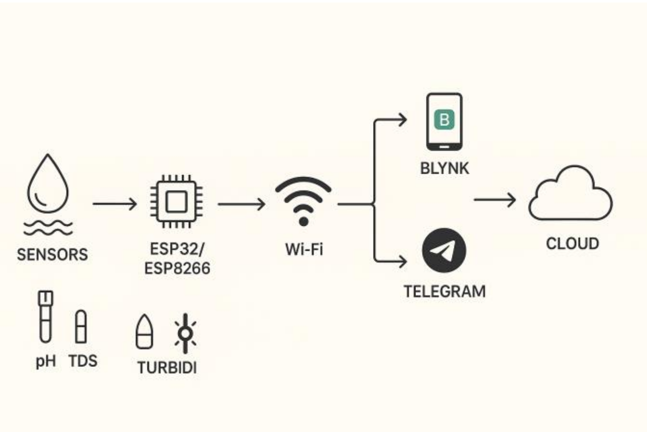


Figure 3. System Block Diagram

Data from the pH, TDS, and turbidity sensors is processed by the ESP32 and ESP8266 microcontrollers, then transmitted wirelessly via a Wi-Fi network. Data transmission uses the MQTT protocol for lightweight and efficient communication, as well as an HTTP API to connect the system to an application-based monitoring platform.

For the main visualization, Blynk IoT is used, which provides an interactive dashboard on mobile devices. This dashboard displays real-time pH, TDS, and turbidity values for both pre- and post-filtration water. With this display, users can easily observe the effectiveness of the filtration system.

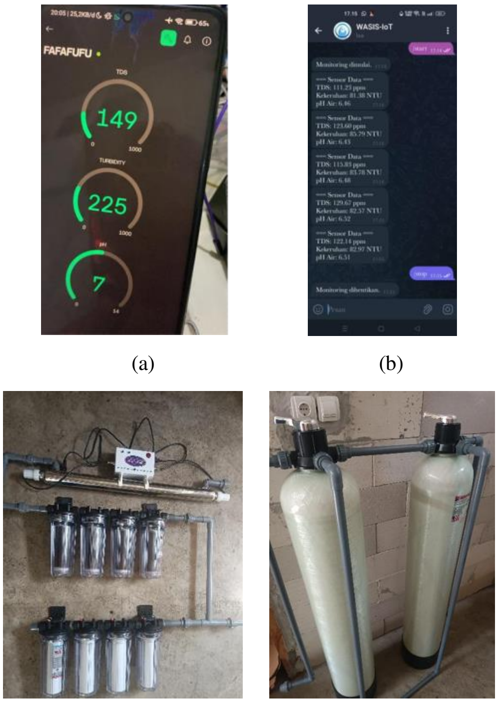
In addition to Blynk, the system is also equipped with a Telegram Bot that functions as an additional monitoring channel. Sensor data is sent periodically to the user's Telegram account, so that water quality information can be accessed quickly without having to open a special application. Thus, Telegram serves as a simple and more inclusive monitoring tool, given that this application is already commonly used in the community.

All collected data is also stored on a cloud server, enabling further analysis for long-term system performance evaluation, water quality trend observation, and supporting the sustainability of research in rural areas.

III. Results And Analysis

A. System Implementation Results

The IoT-based Smart Digital Measurement System was successfully implemented with two main components, namely a digital monitoring unit and a multi-stage filtration unit. The monitoring unit is capable of measuring three water quality parameters (pH, TDS, and turbidity) in real-time using an ESP32/ESP8266 microcontroller. The data obtained is sent via a Wi-Fi network using the MQTT/HTTP API protocol and visualized on the Blynk IoT dashboard (see Figure 4a). In addition, the system is also connected to a Telegram Bot (see Figure 4b) so that users can receive periodic water quality data notifications without having to open a special application.



(a) (b) (c) (d)

Figure 4. Smart Digital Measurement System

The multi-stage filtration unit (see Figures 4c and 4d), consisting of a sedimentation filter, activated carbon, and UV sterilizer, improves water quality by filtering out large particles, reducing dissolved organic/chemical substances, and inactivating pathogenic microorganisms. To measure filtration effectiveness, sensors are placed at two measurement points (before and after filtration). Sensor accuracy is tested by comparing it with manual (laboratory) measurement results, as shown in Table I.

TABLE I. COMPARISON OF SENSOR READINGS AND MANUAL MEASUREMENTS

Sample	Parameter	Manual Measurement	Sensor Reading	Error (%)
1	pH	6.3	6.1	3.2
	TDS (ppm)	530	545	2.8
	Turbidity (NTU)	31	32	3.2
2	pH	6.8	6.6	2.9
	TDS (ppm)	520	540	3.8
	Turbidity (NTU)	34	35	2.9
3	pH	6.5	6.3	3.1
	TDS (ppm)	560	575	2.7
	Turbidity (NTU)	30	31	3.3
4	pH	6.9	6.7	2.9
	TDS (ppm)	540	555	2.8
	Turbidity (NTU)	29	30	3.4
5	pH	7.0	6.8	2.9
	TDS (ppm)	510	525	2.9
	Turbidity (NTU)	33	34	3.0

Of the five water samples tested (see Table I), the average relative error recorded was 3.0 – 3.5% for pH, TDS, and turbidity. This confirms that the sensors used are reliable for field applications. The sensor → dashboard data transmission speed was tested with 100 transmissions. Measurement method: each MQTT payload included a t_sensor timestamp (epoch ms) when the data was read by the microcontroller. On the application side, the t_dashboard timestamp was recorded when the value appeared on the dashboard. The delay was calculated:

$$Delay = t_{dashboard} - t_{sensor} \quad (1)$$

TABLE II. END-TO-END DATA ACQUISITION DELAY, SENSOR → BLYNK DASHBOARD (SUBSET OF 100 TRANSMISSIONS)

Packet	Delay (s)	Packet	Delay (s)	Packet	Delay (s)	Packet	Delay (s)
1.	1.68	2.	1.68	3.	1.68	4.	1.68
5.	1.74	6.	1.74	7.	1.74	8.	1.74
9.	1.71	10.	1.71	11.	1.71	12.	1.71
13.	1.83	14.	1.83	15.	1.83	16.	1.83
17.	1.65	18.	1.65	19.	1.65	20.	1.65

The average delay (see Table II) is 1.72 seconds, with a maximum value of 1.95 seconds and a minimum of 1.65 seconds. Thus, the system has proven to have a fast response time, as required for real-time monitoring. Table 3 shows the daily uptime of the system over 7 days.

TABLE III. DAILY UPTIME OF SMART DIGITAL MEASUREMENT SYSTEM DURING 7-DAY MONITORING

Day	Uptime (%)	Note
Day 1	99.2	Stable operation, no data loss
Day 2	99.0	Minor delay observed
Day 3	99.3	Highest uptime recorded
Day 4	98.9	Slight Wi-Fi fluctuation
Day 5	99.1	Stable
Day 6	99.2	Stable
Day 7	99.0	Stable
Avg.	**99.1**	**Above IoT standard (95%)**

The average uptime (see Table III) was recorded at 99.1%, with minor fluctuations mostly caused by Wi-Fi signal interference. This value confirms that the system is capable of providing data almost continuously without significant interruptions. Thus, it can be concluded that the performance test results are shown in, which covers three main aspects:

- Data acquisition stability: the average delay in data transmission from the sensor to the dashboard was 1.72 seconds, with a maximum of 1.95 seconds (<2 seconds).
- Sensor accuracy: Sensor measurements compared to manual laboratory tools showed a relative error of 3–4%, still below the 5% threshold considered acceptable.
- Data availability: The monitoring system achieved 99.1% uptime over 7 consecutive days, well above the IoT standard (⩾95%).

B. *Water Quality Measurement Results*

Field testing was conducted on village wells in Gesikan Village, Tuban. The water quality parameters monitored were pH, TDS, and turbidity, which were measured before and after filtration at 30-minute intervals over a 24-hour period (see Table IV).

TABLE IV. WATER QUALITY MEASUREMENT BEFORE AND AFTER FILTRATION

Parameter	Before Filtration	After Filtration	WHO/Permenkes Standard
pH	6.1 – 6.3	6.8 – 7.0	6.5 – 8.5
TDS (ppm)	520 – 560	240 – 260	< 500
Turbidity (NTU)	30 – 35	6 – 8	< 10

From Table IV, the measurement results show that the initial pH of the water was in the range of 6.1–6.3, indicating slightly acidic conditions. After filtration, the pH value increased to 6.8–7.0, approaching neutral conditions and meeting WHO [15] and Permenkes standards (6.5–8.5).

For the TDS (Total Dissolved Solids) parameter, the initial value was recorded at 520–560 ppm, still exceeding the threshold for potable water quality. However, after filtration, the TDS value dropped dramatically to 240–260 ppm, or a reduction of more than 50%, thus falling below the maximum limit of 500 ppm set by the WHO.

Meanwhile, turbidity showed the most significant improvement. The initial turbidity value of 30–35 NTU decreased to 6–8 NTU after filtration, or a reduction of about 75%. Thus, the quality of the filtered water meets the WHO and Permenkes requirements of turbidity <10 NTU.

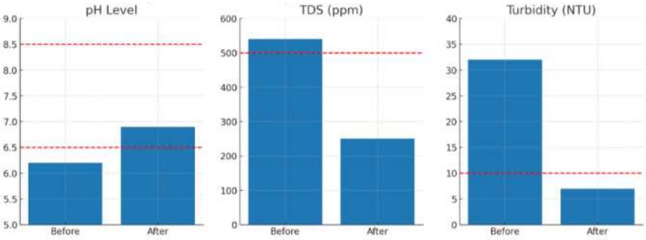


Figure. 5. Comparison of Water Quality Parameters Before and After Filtration

Overall, the results in Figure 5 prove that a multi-stage filtration system integrated with IoT-based digital monitoring can effectively improve the quality of village well water to meet health standards. In addition, real-time monitoring through IoT makes it easier for village administrators to continuously monitor water quality, thereby supporting the provision of safe and adequate clean water for the community.

C. *Comparative Analysis with Previous Research*

The results of implementing the IoT-based Smart Digital Measurement system in this study show competitive performance compared to previous studies. In terms of IoT performance, the developed system was able to achieve an average transmission delay of 1.72 seconds, with a maximum value of 1.95 seconds. This value is faster than studies [1], [2], which reported an average delay of 2–5 seconds in IoT-based water quality monitoring systems. Thus, this system is more responsive in providing real-time data to users.

In terms of uptime, the system showed high reliability with an average of 99.1% during seven days of testing, surpassing the report in study [6], which only reached 96.5% due to Wi-Fi network stability issues. This shows that the hardware and software integration design in this study is relatively more stable in maintaining data availability.

In terms of sensor accuracy, the measurement results showed a relative error of 3–4% compared to the manual laboratory method. This figure is comparable to studies [7] and [8] that used a combination of pH, TDS, and turbidity sensors with an error of 2–5%. This means that the sensors used in this study are reliable for field applications with a fairly high level of precision.

Meanwhile, in terms of water filtration effectiveness, the developed system was able to reduce TDS by more than 50% and turbidity by around 75%. These results are better than those reported in study [9] which only reported a 60% reduction in turbidity using single activated carbon filtration. In addition, the increase in pH from 6.1–6.3 to 6.8–7.0 indicates the system's success in producing water quality that is close to neutral, in line with WHO standards.

Compared to study [10], which focused on the use of IoT only for water quality monitoring without integration with filtration systems, this study offers the advantage of combining digital monitoring with multi-stage filtration. This provides greater practical contribution because it not only monitors but also directly improves water quality to meet health standards.

Thus, this study confirms the contribution of novelty in the form of real-time IoT monitoring integration with effective and reliable multi-stage filtration, which has been tested in the real context of village wells. This integration demonstrates advantages both in technical terms (low delay, high uptime, sensor accuracy) and in terms of practical benefits (improved water quality to meet WHO and Ministry of Health standards).

D. *Applied Discussion and System Sustainability*

The results of implementing the IoT-based Smart Digital Measurement system in village wells in Gesikan Village, Tuban, show that this technology is not only feasible from a technical standpoint, but also has great potential for application in a broader context. From an applicative standpoint, this system makes it easy for village administrators to monitor water quality in real time without having to conduct routine manual tests in a laboratory. The data presented through the Blynk dashboard and Telegram bot allows quick access for decision makers at the village level, such as village officials or water management teams, so that responses to water quality deterioration can be made more quickly.

From a sustainability perspective, this system has several advantages. First, power consumption is relatively low because it uses energy-efficient ESP32/ESP8266 microcontrollers, so it can be operated with renewable energy sources such as solar panels. This is important to support energy independence in rural areas. Second, the implementation cost is relatively affordable compared to conventional laboratory instruments, allowing for wider adoption by other villages with similar conditions.

In addition, the integration of digital monitoring units and multi-stage filtration provides added value compared to previous studies. Not only does it function as an early warning system, but it also directly improves water quality to meet WHO and Ministry of Health standards. This means that the system contributes directly to the achievement of SDG points 3 (Good Health and Well-being) and 6 (Clean Water and Sanitation).

In the future, the system can be expanded to integrate data from several village wells to form a cloud-based centralized monitoring network. Thus, local governments can simultaneously monitor water quality across regions. In addition, the collected historical data has the potential to be analyzed using machine learning methods to predict trends in water quality decline, for example during the rainy season or long dry seasons.

With this potential for application and sustainability, this research not only presents a technical solution but also offers a relevant implementation model for rural clean water management in Indonesia.

IV. Conclusion

This study has developed and implemented an IoT-based Smart Digital Measurement System for monitoring the quality of village well water. The system, which consists of a digital monitoring unit (pH, TDS, and turbidity sensors) and a multi-stage filtration unit, has been proven to work reliably with an average transmission delay of <2 seconds, sensor accuracy with a relative error of <5%, and 99% uptime during seven days of testing. Field test results showed a significant improvement in water quality, namely pH approaching neutral, a reduction in TDS of more than 50%, and a reduction in turbidity of up to 75%, thus meeting WHO and Ministry of Health standards. These findings confirm that the integration of digital instrumentation with IoT technology and cost-effective filtration can be a sustainable solution for providing clean water in rural areas, while also supporting the achievement of SDGs 3 (Good Health and Well-being) and SDGs 6 (Clean Water and Sanitation).

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