IoT-Based Rainfall Monitoring System Using a Tipping Bucket Rain Gauge Sensor and ESP32 DevKit V1

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Abstract
Rainfall is one of the most important hydrometeorological parameters used in weather observation, water resource management, and disaster mitigation. Accurate and real-time rainfall information is essential for environmental monitoring and decision-making. This study aims to develop an Internet of Things (IoT)-based rainfall monitoring system using a tipping bucket rain gauge sensor, ESP32 DevKit V1, LCD I2C, and the ThingSpeak cloud platform. The proposed system measures rainfall automatically, processes the data using ESP32, displays the results on an LCD, and transmits the data via Wi-Fi to ThingSpeak for real-time monitoring. The measurement results were validated using rainfall observations from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). Experimental results showed that the developed system successfully performed rainfall measurement, cloud-based data transmission, and online monitoring. The validation process resulted in an average error of 1.38% and an average accuracy of 98.62%, indicating that the proposed system provides reliable rainfall measurements. Therefore, the developed system can serve as an alternative solution for real-time rainfall monitoring applications.

1. Introduction

Rainfall is one of the most important hydrometeorological parameters because it significantly influences agriculture, water resource management, flood mitigation, environmental sustainability, and weather forecasting. Accurate rainfall information is essential for supporting decision-making in various sectors, particularly in regions that frequently experience climate variability and extreme weather events. In Indonesia, rainfall varies considerably due to seasonal and geographical conditions. Therefore, continuous rainfall observation is necessary to provide reliable data for environmental monitoring and disaster risk reduction. Therefore, continuous rainfall observation is necessary to provide reliable data for environmental monitoring and disaster risk reduction [1], [2], [3], [4], .

Conventional rainfall monitoring generally relies on manual observations or automatic weather stations with limited spatial coverage [2], [5], [6]. Although these methods provide reliable measurements, rainfall distribution may differ even within relatively short distances because of local topographical and atmospheric conditions. As a result, data collected from a single observation station may not accurately represent rainfall conditions in surrounding areas. This limitation highlights the need for additional rainfall monitoring systems that can provide location-specific observations with continuous data acquisition.

The rapid advancement of the Internet of Things (IoT) has significantly transformed environmental monitoring by enabling automatic data collection, wireless communication, cloud storage, and remote visualization. IoT technology integrates sensors, embedded systems, internet connectivity, and cloud computing into a unified platform that allows environmental parameters to be monitored in real-time. Compared with conventional monitoring approaches, IoT-based systems reduce human intervention, improve operational efficiency, and provide continuous access to measurement data through internet-connected devices [7], [8], [9], [10].

Among various environmental monitoring applications, rainfall observation has become one of the most important fields for IoT implementation. The integration of rainfall sensors with wireless communication technology enables automatic measurement, processing, and transmission of rainfall data without requiring manual recording. Consequently, rainfall information can be accessed remotely, stored automatically in cloud databases, and analyzed continuously to support hydrological studies and disaster mitigation activities [1], [8], [5], [6].

A tipping bucket rain gauge is one of the most widely used rainfall sensors because of its simple construction, low implementation cost, and compatibility with digital monitoring systems. The sensor operates by collecting rainwater into a small bucket that tips whenever a predetermined water volume is reached. Each tipping movement generates an electrical pulse, which is counted by a microcontroller and converted into rainfall depth. This measurement principle allows rainfall to be recorded automatically with satisfactory accuracy while requiring relatively simple maintenance procedures [11], [2], [5], [6], [12].

In this study, the rainfall monitoring system employs the ESP32 DevKit V1 as the primary microcontroller because it integrates Wi-Fi communication, adequate processing capability, and low power consumption into a compact platform. The ESP32 receives pulse signals generated by the tipping bucket rain gauge sensor, calculates rainfall intensity, displays measurement results on an LCD I2C module, and transmits the collected data to the ThingSpeak cloud platform through a wireless internet connection. The use of ThingSpeak enables real-time visualization, cloud storage, and historical data retrieval, thereby improving the accessibility of rainfall information [13], [14], [7], [15], [9], [16].

Several previous studies have successfully implemented IoT-based rainfall monitoring systems using ESP32 microcontrollers and cloud platforms. These studies demonstrated that IoT technology is capable of transmitting rainfall data in real-time while reducing the need for manual observations. However, many previous studies mainly emphasized system implementation and cloud-based monitoring without comprehensively validating sensor measurements against official meteorological observations. Consequently, the reliability of measurement results has not been fully evaluated under actual environmental conditions [1], [7], [5], [6], [17].

To address these limitations, this study proposes an Internet of Things (IoT)-based rainfall monitoring system utilizing a tipping bucket rain gauge sensor, ESP32 DevKit V1, LCD I2C, and the ThingSpeak cloud platform. Unlike several previous studies, the developed system not only performs automatic rainfall monitoring but also validates its measurements using official rainfall observations published by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). The performance of the proposed system is evaluated through percentage error and measurement accuracy analyses to determine its reliability for real-time environmental monitoring applications. The experimental results demonstrate that the developed system achieved an average error of 1.38% and an average accuracy of 98.62%, indicating that it provides reliable rainfall measurements for practical environmental monitoring applications [2], [8], [16].

2. Research Methods

This study employed an experimental research method to design, implement, and evaluate an Internet of Things (IoT)-based rainfall monitoring system. The research consisted of four main stages, namely system design, hardware implementation, software development, and system evaluation. The proposed system was designed to automatically measure rainfall using a tipping bucket rain gauge sensor, process the measurement data through an ESP32 DevKit V1 microcontroller, display the results locally using an LCD I2C module, and transmit the collected data to the ThingSpeak cloud platform for real-time monitoring. Finally, the measurement results were validated using official rainfall observations published by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) [1], [7], [3], [5],

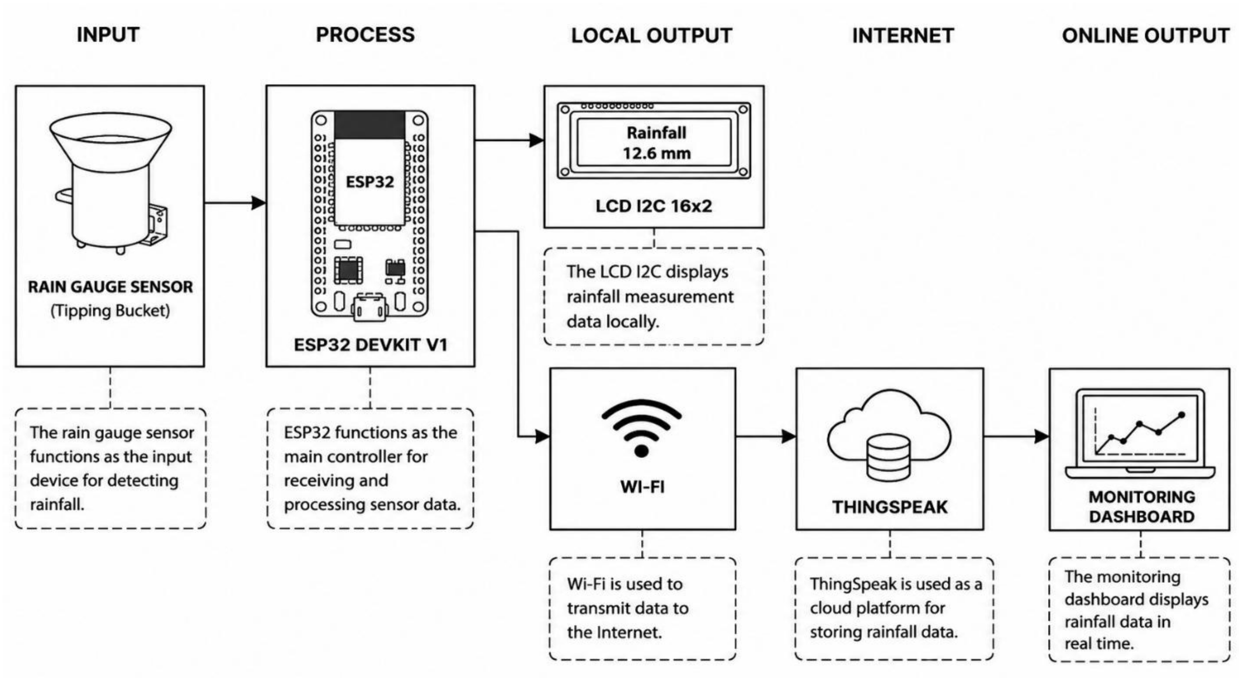


Fig. 1. System Architecture of the Proposed IoT-Based Rainfall Monitoring System

Figure 1 illustrates the overall architecture of the proposed IoT-based rainfall monitoring system. The system consists of four primary components: the tipping bucket rain gauge sensor, ESP32 DevKit V1, LCD I2C display, and the ThingSpeak cloud platform. Rainfall is first detected by the rain gauge sensor and converted into electrical pulse signals corresponding to bucket tipping events. These pulse signals are processed by the ESP32 to rainfall amount based on the predefined sensor resolution [18], [14], [5], [7].

After processing the measurement data, the ESP32 simultaneously displays the rainfall value on the LCD I2C module and transmits the collected information to the ThingSpeak cloud server through a Wi-Fi connection. The cloud platform stores the received data and visualizes it in graphical form, allowing users to monitor rainfall conditions remotely using any internet-connected device [7], [15], [19].

Table 1. Hardware Components Used in the Proposed Monitoring System

Component	Specification
Rain Gauge Sensor	Tipping Bucket
Microcontroller	ESP32 DevKit V1
Display	LCD 16×2 I2C
Communication	Wi-Fi

Cloud Platform	ThingSpeak
Power Supply	USB 5 V

Table I presents the hardware components used in the proposed rainfall monitoring system. The tipping bucket rain gauge sensor functions as the primary sensing device for rainfall measurement, while the ESP32 DevKit V1 serves as the main processing and communication unit. An LCD I2C module provides local visualization of measurement results, whereas ThingSpeak acts as the cloud platform responsible for data storage and real-time visualization. The selected hardware components were chosen because they provide an appropriate balance between measurement capability, implementation cost, ease of integration, and wireless communication performance. Furthermore, the ESP32 integrated Wi-Fi module eliminates the need for additional communication hardware, thereby simplifying the overall system architecture [13], [7], [15], [5], [16].[20]

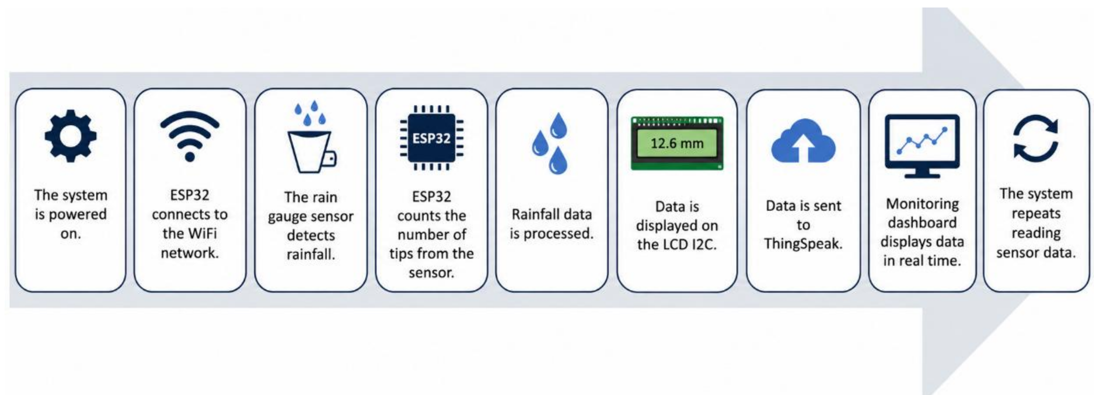


Fig. 2. Flowchart of the Proposed Rainfall Monitoring System

Figure 2 presents the operational flow of the developed rainfall monitoring system. The monitoring process begins when the ESP32 is powered on and establishes a Wi-Fi connection. Once the network connection has been successfully established, the system continuously monitors the tipping bucket rain gauge sensor. The sensor detects rainfall events and generates electrical pulse signals corresponding to each bucket tip. These pulse signals are processed by the ESP32 to calculate the rainfall amount based on the predefined sensor resolution. The calculated rainfall values are displayed on the LCD I2C module and transmitted to the ThingSpeak cloud platform for real-time monitoring and data storage [13], [7], [15], [5], .

Rainfall Calculation

The rainfall value was calculated based on the tipping bucket principle. Each bucket tip corresponds to a rainfall resolution of 0.30 mm. Therefore, the total rainfall was obtained by multiplying the number of bucket tipping events by the sensor resolution configured for the rain gauge sensor. The rainfall calculation is presented in Equation (1) [11], [5], [6],.

$$CH = n \times k \qquad 1$$

where:
CH = Rainfall (mm)
n = Number of bucket tips
k = Sensor resolution (0.30 mm/tip).

Equation (1) was used to calculate the rainfall amount recorded by the proposed monitoring system. The calculated rainfall values were subsequently displayed on the LCD I2C module and transmitted to the ThingSpeak cloud platform for real-time monitoring. These rainfall measurements were further used as the primary dataset for comparison with the official rainfall observations provided by BMKG [7], [15], [5], [3].

Error Calculation

To evaluate the performance of the proposed monitoring system, the rainfall measurements obtained from the IoT device were compared with the official rainfall observations published by BMKG. The percentage error was calculated to determine the deviation between the measured rainfall values and the reference observations, as presented in Equation (2) [5], [3].

$$Error(\%) = \frac{|X_i - X_b|}{X_b} \times 100\% \quad (2)$$

where:
Xi = IoT rainfall measurement (mm)
Xb = BMKG rainfall measurement (mm)

The calculated percentage error indicates the deviation between the proposed monitoring system and the BMKG reference observations. A smaller error value indicates better agreement between the measured rainfall and the reference data, demonstrating improved system performance.

Accuracy Calculation

Following the error analysis, the measurement accuracy of the proposed rainfall monitoring system was determined. The system accuracy was calculated by subtracting the percentage error from one hundred percent, as expressed in Equation (3) [5], [3].

$$Accuracy(\%) = 100\% - Error(\%) \quad (3)$$

where:
Accuracy = System accuracy (%)
Error = Percentage error (%)

The calculated accuracy was used to evaluate the overall reliability of the proposed IoT-based rainfall monitoring system. The average error and average accuracy obtained from all observation data were subsequently used to assess whether the developed system was suitable for real-time rainfall monitoring applications [3], [5].

Results and Discussion

3.1 Hardware Implementation

This section presents the implementation and performance evaluation of the proposed Internet of Things (IoT)-based rainfall monitoring system. The developed system consists of a tipping bucket rain gauge sensor, an ESP32 DevKit V1 microcontroller, an LCD I2C module, and the ThingSpeak cloud platform. System performance was evaluated through hardware implementation, real-time cloud monitoring, and validation against official rainfall observations provided by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). The evaluation focused on determining the reliability of the developed monitoring system for real-time environmental monitoring applications.

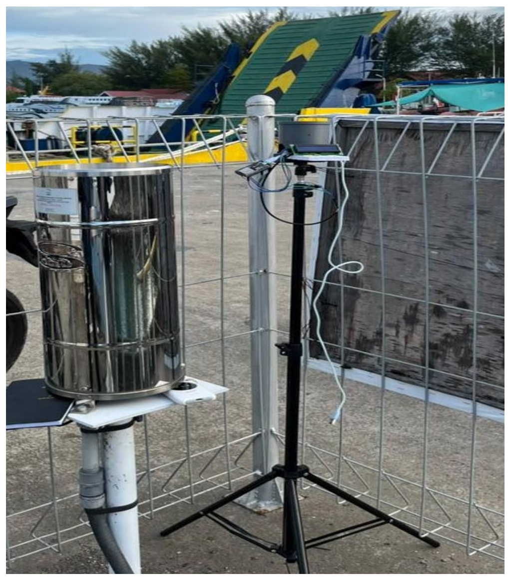
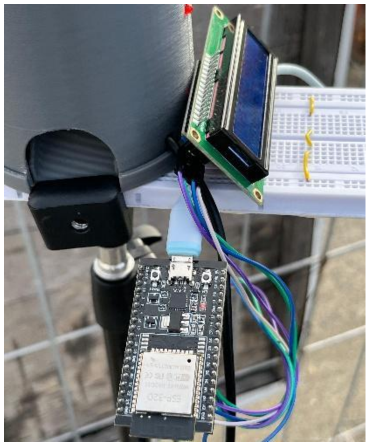


Fig. 3. Hardware Implementation of the Proposed IoT-Based Rainfall Monitoring System

Figure 3 shows the hardware implementation of the proposed IoT-based rainfall monitoring system installed at the observation site. The system consists of a tipping bucket rain gauge sensor mounted on a supporting structure, an ESP32 DevKit V1 enclosed in a protective casing, and an LCD I2C module for local display. The hardware components were integrated to ensure continuous rainfall measurement and reliable wireless data transmission.

The tipping bucket rain gauge sensor continuously detects rainfall events and generates pulse signals corresponding to each bucket tipping movement. These pulse signals are processed by the ESP32 to calculate the rainfall amount. The calculated rainfall values are then displayed on the LCD I2C module while simultaneously being transmitted through a Wi-Fi connection to the ThingSpeak cloud platform. The successful implementation demonstrates that the developed hardware operates reliably under outdoor environmental conditions.



(a) ESP32 DevKit V1 with LCD I2C

(b) tipping bucket rain gauge sensor

(c) LCD I2C displaying Wi-Fi connection status

(d) complete hardware implementation

Fig. 4. Main Hardware Components of the Proposed IoT-Based Rainfall Monitoring System: (a) ESP32 DevKit V1 with LCD I2C, (b) tipping bucket rain gauge sensor, (c) LCD I2C displaying Wi-Fi connection status, and (d) complete hardware implementation.

Figure 4 illustrates the main hardware components used in the proposed rainfall monitoring system. Figure 4(a) shows the ESP32 DevKit V1 connected to the LCD I2C module, which functions as the primary processing and communication unit. Figure 4(b) presents the tipping bucket rain gauge sensor employed to detect rainfall by collecting rainwater and producing electrical pulse signals during bucket tipping events.

Figure 4(c) displays the LCD I2C module indicating that the ESP32 has successfully established a Wi-Fi connection before transmitting rainfall measurements to the cloud platform. Meanwhile, Figure 4(d) presents the complete hardware implementation of the developed monitoring system during field deployment. The successful integration of these components demonstrates that the proposed monitoring system operated properly throughout the observation period and was capable of performing automatic rainfall monitoring under outdoor environmental conditions.

3.2 ThingSpeak Cloud Monitoring

This subsection presents the implementation of the ThingSpeak cloud platform for real-time rainfall monitoring. After the hardware components were successfully integrated, the developed monitoring system automatically transmitted rainfall measurements from the ESP32 DevKit V1 to the ThingSpeak cloud platform through a Wi-Fi connection. The uploaded data were stored continuously and visualized in graphical form, enabling remote monitoring throughout the observation period.

Fig. 5. Rainfall Monitoring Graph Displayed on the ThingSpeak Cloud Platform

Figure 5 presents the rainfall monitoring graph displayed on the ThingSpeak cloud platform during the observation period. The graph shows that the developed monitoring system successfully transmitted rainfall measurements from the ESP32 DevKit V1 through a Wi-Fi connection. The uploaded rainfall data were automatically stored and visualized on the cloud platform, allowing users to monitor rainfall conditions remotely throughout the observation period.

The graphical visualization demonstrates that the proposed monitoring system maintained stable communication with the ThingSpeak platform during the monitoring period. The recorded rainfall data were continuously updated and stored, providing historical rainfall information that can be used for further analysis and evaluation of system performance.

3.3 Comparison of Rainfall Measurements

This subsection presents a comparison between the daily rainfall measurements obtained from the proposed IoT-based rainfall monitoring system and the official daily rainfall observations published by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). The comparison was conducted to evaluate the measurement performance of the developed monitoring system under actual environmental conditions and to determine its reliability in measuring daily rainfall.

Table 2. Comparison of IoT and BMKG Rainfall Measurements

Date	IoT Rainfall Measurement (mm)	BMKG Rainfall (mm)	Rainfall Category
1 May	0	0	No Rain
2 May	7.6	7.8	Light Rain
3 May	0.4	0.4	Very Light Rain
4 May	0	0	No Rain
5 May	0.2	0.2	Very Light Rain
6 May	0	0	No Rain
7 May	2.7	2.8	Very Light Rain
8 May	24.1	24.4	Moderate Rain
9 May	10.9	11	Light Rain

Date	IoT Rainfall Measurement (mm)	BMKG Rainfall (mm)	Rainfall Category
10 May	7.5	7.6	Light Rain
11 May	0.2	0.2	Very Light Rain
12 May	1	1	Very Light Rain
13 May	0.2	0.2	Very Light Rain
14 May	17	17.2	Light Rain
15 May	1.8	1.8	Very Light Rain
16 May	0.4	0.4	Very Light Rain
17 May	0	0	No Rain
18 May	0	0	No Rain
19 May	0	0	No Rain
20 May	9.9	10	Light Rain
21 May	1.3	1.4	Very Light Rain
22 May	0	0	No Rain
23 May	0	0	No Rain
24 May	0	0	No Rain
25 May	0	0	No Rain
26 May	3.1	3.2	Very Light Rain
27 May	0	0	No Rain
28 May	0	0	No Rain
29 May	0	0	No Rain
30 May	0	0	No Rain
31 May	0	0	No Rain

Table II shows that the IoT measurements closely correspond to the BMKG reference data on nearly all observation days. The observed differences are relatively small and may be attributed to the mechanical characteristics of the tipping bucket, environmental factors such as wind and uneven rainfall distribution, and minor variations in the timing of rainfall events. The rainfall categories produced by the system are also consistent with the BMKG data, ranging from no rain to moderate rain.

Although slight differences were observed between the proposed system and the BMKG reference data, these deviations remained small throughout the observation period and can be attributed to the mechanical characteristics of the tipping bucket rain gauge, environmental factors such as wind and uneven rainfall distribution, and minor variations in the timing of rainfall events. Despite these limitations, the system maintained consistent performance and reliably identified rainfall conditions ranging from no rain to moderate rain. The strong agreement in both measured values and rainfall classifications confirms that the developed system provides not only accurate measurements but also meaningful rainfall information for environmental monitoring applications.

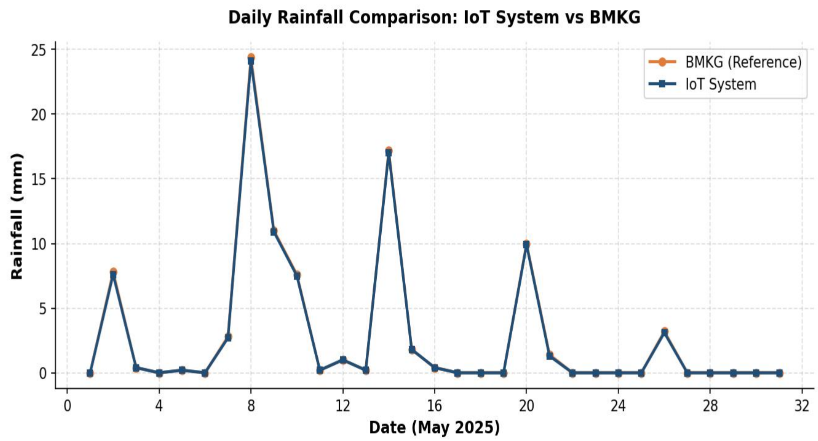


Fig. 6. Daily Rainfall Comparison of the IoT System against BMKG

Figure 6 visualizes the Table 2 data as a line chart. The two curves are nearly coincident throughout the observation period, showing that the rainfall pattern recorded by the IoT system is highly aligned with the BMKG reference, including at the highest peak on 8 May at 24.1 mm (IoT) versus 24.4 mm (BMKG).

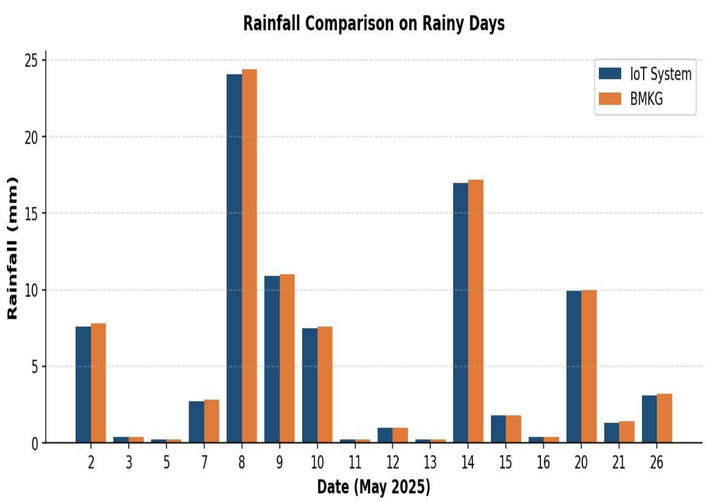


Fig. 7a Rainfall Comparison on Rainy Days

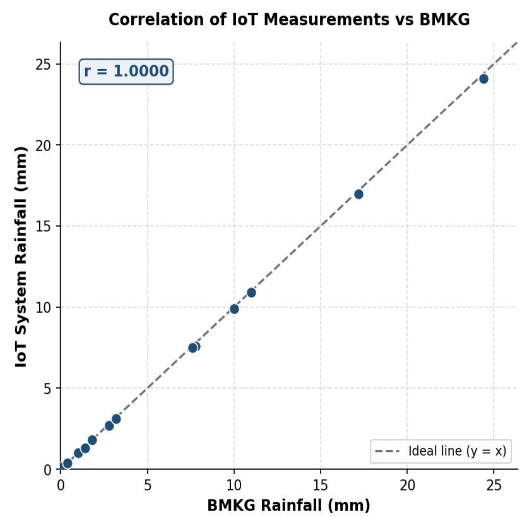


Fig. 7b. Correlation of IoT Measurements against BMKG

Figure 7a. highlights only the rainy days so that the deviation between the two systems is easier to observe. The difference on each rainy day is consistently small, generally below 0.3 mm, confirming the precision of the system across various rainfall intensities. Figure7b. shows the scatter plot between the IoT and BMKG measurements. The observation points cluster tightly around the ideal line y = x with a correlation coefficient close to unity, confirming a strong linear relationship and the consistency of the system measurements with the official reference data.

3.4 Error and Accuracy Analysis

This subsection presents the error and accuracy analysis of the proposed IoT-based rainfall monitoring system. The evaluation was performed by comparing the rainfall measurements obtained from the developed monitoring system with the official rainfall observations published by BMKG. The percentage error and measurement accuracy were calculated to evaluate the performance and reliability of the developed monitoring system.

Table 3. Error and Accuracy of The Proposed IoT-Based Rainfall Monitoring System

Parameter	Value
Average Percentage Error	1.38%
Average Measurement Accuracy	98.62%

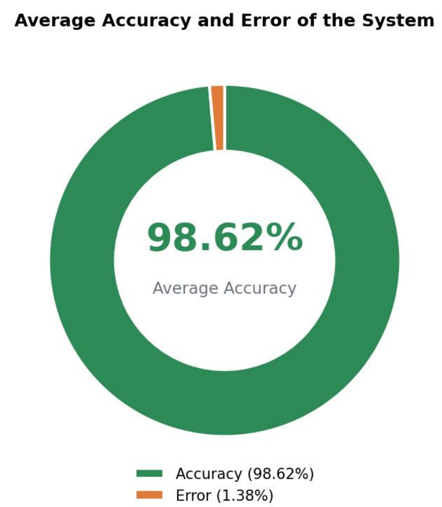


Table III summarizes the percentage error and measurement accuracy obtained from the comparison between the proposed IoT-based rainfall monitoring system and the official BMKG observations. The developed monitoring system achieved an average percentage error of 1.38% and an average measurement accuracy of 98.62%. These results indicate that the developed system provides highly reliable rainfall measurements throughout the observation period.

The relatively low percentage error demonstrates that the rainfall measurements produced by the proposed monitoring system are highly consistent with the BMKG reference data. The integration of the tipping bucket rain gauge sensor, ESP32 DevKit V1, and ThingSpeak cloud platform successfully provided stable rainfall monitoring with satisfactory measurement performance. The obtained results confirm that the developed monitoring system is capable of performing continuous rainfall monitoring under actual environmental conditions.

Compared with previous studies on IoT-based environmental monitoring systems, the proposed monitoring system achieved competitive measurement accuracy while maintaining a simple hardware configuration and low implementation cost. Therefore, the developed system can be considered suitable for real-time rainfall monitoring applications, particularly in locations requiring continuous observation and cloud-based data accessibility.

3. Conclusions

This study successfully developed an Internet of Things (IoT)-based rainfall monitoring system utilizing a tipping bucket rain gauge sensor, ESP32 DevKit V1, LCD I2C, and the ThingSpeak cloud platform. The proposed system was capable of automatically measuring rainfall, displaying measurement results locally, transmitting rainfall data through a Wi-Fi network, and providing real-time visualization using the cloud platform. The integration of these components enabled continuous rainfall monitoring with minimal human intervention while improving the accessibility of rainfall information.

Performance evaluation demonstrated that the developed monitoring system produced reliable measurement results when validated against official rainfall observations published by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). The system achieved an average percentage error of 1.38% and an average accuracy of 98.62%, indicating strong agreement with the reference observations. Therefore, the proposed system can be considered an effective, low-cost, and reliable solution for real-time rainfall monitoring applications.

Future work may focus on integrating additional environmental sensors, such as temperature, humidity, wind speed, and atmospheric pressure sensors, to develop a more comprehensive weather monitoring system. Furthermore, implementing alternative cloud platforms and mobile applications may improve data accessibility, system scalability, and user interaction for broader environmental monitoring applications.

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