

Original Research

Implementation of An IoT-Based Temperature and Humidity Monitoring System with Data Logging Features in the Calibration Laboratory

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ABSTRACT

ISO/IEC 17025:2017 accredited calibration laboratory, holds an absolute obligation to monitor, control, and record environmental conditions (temperature and humidity) to maintain the validity of measurement results and support budget uncertainty calculations. However, the current monitoring system is still conventional and manual (three times a day), making it vulnerable to human errors, data duplication, and an inability to record fluctuations between intervals. This study aims to design and build an automatic temperature and humidity monitoring system based on the Internet of Things (IoT) featuring a dual-logging system to ensure continuous technical records. The system design utilizes an ESP32 microcontroller as the central processing unit, a DHT11 sensor to detect ambient temperature and relative humidity, a Micro SD Card module as a local backup media (offline backup), and the ThingSpeak platform as a cloud database for remote monitoring. The sensor data is saved to the SD Card in CSV format every 5 minutes, while data transmission to ThingSpeak is scheduled every 1 minute. System testing involved functionality tests (Black Box Testing), local storage capability tests, connectivity tests, data validity tests, and stability/durability tests. The results indicate that the IoT-based monitoring device was successfully functionality test success rate. The implementation of the dual-logging feature effectively preserves the integrity and continuity of records; ThingSpeak simplifies real-time data visualization, while the Micro SD Card operates as a reliable local failsafe during network fluctuations. This system minimizes human error, increases operational oversight efficiency, and supports regulatory compliance with Clauses 6.3 and 7.5 of ISO/IEC 17025:2017.

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1. INTRODUCTION

Companies providing instrumentation and calibration services are required to maintain reliable measurement processes and appropriate environmental conditions to support the quality of calibration activities. In testing and calibration laboratories, temperature and relative humidity are among the environmental parameters that need to be monitored because changes in these conditions may affect measurement processes and the validity of measurement results. ISO/IEC 17025:2017 therefore requires laboratories to monitor, control, and record environmental conditions when they can influence the validity of results [1]. Recent research has also demonstrated the importance of continuous environmental monitoring in laboratories to support compliance with ISO/IEC 17025 requirements and to provide documented environmental records [2].

In the calibration laboratory investigated in this study, environmental monitoring was previously conducted using a conventional procedure. Laboratory personnel read an analog thermo-hygrometer three times a day and manually recorded the measured temperature and humidity values in a paper logbook. Such periodic recording provides measurements at specific observation times, but environmental changes occurring between recording intervals may not be represented in the technical records. Similar conditions have been reported in recent laboratory studies, where conventional manual monitoring has been associated with periodic data collection and greater dependence on operator intervention [3,4]. Consequently, an automated monitoring approach can provide a more continuous representation of environmental conditions while reducing the need for repeated manual observation.

Manual data recording can also introduce transcription and data-entry errors when measurement values are first written on paper and subsequently transferred to an electronic system. A recent prospective study in a laboratory environment demonstrated that conventional paper-based recording involves an additional transcription step before the data are stored electronically, creating a potential source of post-analytical transcription errors [5]. The study further showed that direct electronic data entry can reduce the number of intermediate data-transfer steps. Therefore, automated acquisition and recording of temperature and humidity measurements can be considered a practical approach for improving the continuity and traceability of environmental records. The application of Internet of Things (IoT) technology provides an opportunity to automate the acquisition, transmission, visualization, and storage of environmental data. Recent studies have implemented IoT-based temperature and humidity monitoring in laboratory environments using microcontrollers, sensors, wireless communication, and web- or cloud-based interfaces [3,4,6]. For example, an IoT system developed for a BMKG calibration laboratory enabled automated temperature and humidity measurement and remote access to environmental information [4]. Other research has implemented IoT-based monitoring in calibration laboratories using ESP8266 or ESP32 platforms, demonstrating the feasibility of real-time environmental monitoring and data acquisition [3,6]. These developments indicate that IoT can support the digitalization of environmental monitoring while providing historical data that can be accessed more efficiently than periodic manual records. Data storage is an important component of an environmental monitoring system because continuous measurement requires reliable mechanisms for retaining historical observations. A data logger can automatically collect and store sensor measurements at predefined intervals, while local storage can provide access to records independently of network availability. Wahyuni et al. developed a multi-sensor data logger based on ESP32 that combined an RTC timing mechanism with SD-card and database storage, demonstrating the practical use of multiple storage media for continuous data acquisition [7]. Similarly, an IoT-based laboratory environmental monitoring system developed in accordance with ISO/IEC 17025 incorporated SD memory for local storage and cloud-based storage for monitoring laboratory conditions [2]. These studies provide a foundation for combining local and remote storage within an environmental monitoring architecture.

In addition to local data storage, cloud platforms can facilitate remote visualization and access to historical measurements. Recent research has demonstrated the use of platforms such as ThingSpeak for real-time temperature and humidity monitoring and data transmission from ESP8266/ESP32-based systems [8]. Such platforms allow measurement data to be visualized remotely and organized as time-series information. However, the availability of cloud-based monitoring is inherently associated with the operational condition of the communication network. A local storage mechanism can therefore complement cloud transmission by retaining measurement records when communication is temporarily unavailable. This combination provides a practical approach for maintaining data continuity while retaining the advantages of remote monitoring.

Based on these considerations, this study develops an IoT-based temperature and humidity monitoring system for a calibration laboratory using an ESP32 microcontroller, a DHT11 sensor, a Micro SD Card, an external RTC module, and the ThingSpeak cloud platform. The proposed system implements a dual-logging architecture in which measurement data are stored locally in CSV format at five-minute intervals while selected data are transmitted to the ThingSpeak platform at one-minute intervals. The local storage functions as an offline backup, whereas the cloud component provides remote visualization of environmental conditions. This architecture is intended to combine continuous local recording with remote monitoring within a single system. The contribution of this study is therefore focused on the practical integration of local and cloud-based data logging for environmental monitoring in the calibration laboratory under investigation. Rather than relying

solely on manual periodic recording or a single storage mechanism, the proposed implementation provides two complementary recording paths that can support continuity of technical records during temporary network disturbances. The system is evaluated through functionality, local storage, connectivity, data validity, and operational stability tests to assess its suitability for continuous temperature and humidity monitoring and its contribution to the documentation of laboratory environmental conditions in accordance with ISO/IEC 17025 requirements [1, 2].

2. RESEARCH METHODS

2.1. Research Framework

The research employed an engineering experimental approach. The stages of the study consisted of preparation and literature review, hardware and data architecture design, physical assembly of components, system programming using the Arduino IDE, configuration of the ThingSpeak cloud platform, and a series of system performance tests [9, 10, 17, 18]. This experimental workflow was systematically designed to validate the performance of the monitoring device before its full implementation in the laboratory.

2.2. Hardware Architecture and Wiring

Cloud-based infrastructures support remote access, data storage, monitoring, and visualization for IoT applications [9, 18]. The hardware architecture of this system is based on a single main microcontroller, namely the ESP32, which processes input from the DHT11 sensor and simultaneously distributes the data to three output components [15, 16, 19]. The interconnection mapping of pins among the main components was designed efficiently to avoid signal noise, as presented in Table 1 [11, 13].

Table 1. ESP32 Pin Mapping with System Components

Component	Component Type	Pin ESP32	Communication Type
Sensor DHT11 OLED 0.96"	VCC, Data, GND VCC, GND, SCL, SDA	3.3V, GPIO 4, GND 3.3V, GND, GPIO 22, GPIO 21	Single-Bus I2C
MicroSD Adapter	MISO, MOSI, SCK, CS	GPIO 19, GPIO 23, GPIO 18, GPIO 5	SPI
RTC Module	SDA, SCL	GPIO 21, GPIO 22	I2C Shared

The system receives its primary power supply from a minimum 5 VDC, 1 A adapter connected directly to the ESP32 micro-USB port to maintain long-term operational stability.

2.3. Proposed Dual-Logging Logic

Data processing in the software is managed using a non-blocking system so that the failure of one function does not interfere with other functions. The microcontroller acquires data from the DHT11 sensor and subsequently processes timestamps obtained from the external RTC module.

a. Local Storage

Data are written to the Micro SD Card in a structured CSV format (Columns: Date, Time, Temperature, Temperature Status, Humidity, Humidity Status) with a sampling interval of every five minutes [11, 13]. The program ensures that the file is opened, written, and immediately closed during each cycle to prevent file corruption. SD Card-based local storage has been implemented effectively in environmental data-logger systems and can provide an additional recording layer when remote communication is unavailable [9, 13].

b. Cloud Storage

In this research, cloud storage uses ThingSpeak, a platform that supports IoT applications and API-based data transmission [12, 15, 20]. Wireless transmission to the ThingSpeak server is scheduled at one-minute intervals. The transmitted data consist of instantaneous (snapshot) data corresponding to the current minute. Access to the cloud database is secured using a private mode through Write API Key authentication. The ThingSpeak interface provides visualization of sensor readings and their corresponding timestamps [15, 20].

2.4. Experimental Setup and Evaluation Metrics

System reliability testing was continuously conducted for a period of seven (7) days directly inside the Calibration Laboratory of one of the companies in Indonesia. System performance was evaluated through five primary metrics: Electrical functionality testing (Black Box Testing); Local storage capability testing (offline logging); Wireless connectivity testing (latency and packet loss); Multi-interface data synchronization validity testing; and Twenty-four-hour operational endurance testing (stress test) [9, 18, 19].

3. RESULTS AND DISCUSSION

3.1. System Realization and Functionality Test

The physical implementation of the IoT-based temperature and humidity monitoring system was successfully realized as an integrated standalone device. Functionality testing using the Black Box Testing method was conducted to ensure the reliability of the electrical interactions among all constituent components. Based on the functionality testing checklist, all circuit blocks, including DHT11 sensor reading, Micro SD SPI initialization, OLED I2C communication, and Wi-Fi data transmission, demonstrated a 100% success rate with normal operational status.

3.2. Data Logging Capability Analysis (Local Storage)

The local data logging feature was tested to validate the performance of the Micro SD Card module as a backup storage medium during offline conditions. The recorded data samples were successfully organized in a neat and structured CSV format. An example of the recorded log data is presented in Table 2.

Table 2. Sample Data Logging Results in Local Micro SD Storage

Date	Time	Temperature (°C)	Temperature Status	Humidity (%)	Humidity Status
07/05/2026	01:00:50	26.6	Good	74	Wet
07/05/2026	01:05:51	26.6	Good	74	Wet
07/05/2026	01:10:52	26.6	Good	74	Wet

Throughout the seven-day testing period, the system successfully performed continuous writing operations without experiencing memory failure issues. The program logic, which immediately closes the file after the writing process, proved effective in maintaining the integrity of textual data against the risk of data loss caused by power supply fluctuations.

3.3. IoT Connectivity and Cloud Transmission Test

Wireless connectivity testing was conducted to evaluate the stability of snapshot data transmission to the ThingSpeak dashboard. The performance of the laboratory Wi-Fi network was analyzed based on latency (response time) and packet loss (the percentage of data packets lost during transmission).

Table 3. Sample Data Logging Results on ThingSpeak Storage

Timestamp	Temperature	Humidity
2026-05-07 23:53:07	23,0	58
2026-05-07 23:54:11	22,9	58
2026-05-07 23:55:20	23,0	58

The transmission data calculations indicated an average update latency of 68.96 seconds to reach the cloud server. Meanwhile, packet loss testing recorded an average value of 12.39%, confirming that the wireless infrastructure in the laboratory area was capable of consistently supporting periodic data transmission every one minute.

3.4. Data Validity and Multi-Interface Consistency

The validity metric was evaluated by comparing parameter values simultaneously displayed across three visualization interfaces: the physical OLED display, the local storage file (.CSV), and the online ThingSpeak dashboard graphs. The comparison results demonstrated perfect data synchronization.

Table 4. Sample Results of the Multi-Interface Validity Test

No.	Testing Time	Sensor Parameter	Value Reading OLED (D_{Acuan})	Value SD Card (D_{Uji})	% Validity (V_d)	Status
1	02/06/2026 19:18	Temperature ($^{\circ}\text{C}$)	27.5	27.5	100.0	Valid
		Humidity (%RH)	80.0	81.0	98.8	Valid
2	02/06/2026 19:23	Temperature ($^{\circ}\text{C}$)	27.5	27.5	100.0	Valid
		Humidity (%RH)	78.0	78.0	100.0	Valid
3	02/06/2026 19:28	Temperature ($^{\circ}\text{C}$)	27.5	27.5	100.0	Valid
		Humidity (%RH)	78.0	78.0	100.0	Valid

The numerical values of temperature and humidity displayed on the OLED were proven to be identical to the raw data stored on the Micro SD Card. Likewise, the snapshot data appearing in the ThingSpeak time-series charts showed precise correspondence with the current-minute data stored locally. This synchronization ensures that there are no numerical deviations or information distortions within the internal system.

3.5. Durability and Stability Analysis (Stress Test)

The system was operated in a fully active mode (continuous active/standby) without sleep mode for a continuous period of 24 hours to evaluate the thermal endurance and logical stability of the microcontroller under constant workloads. The 24-hour monitoring results indicated that the system was capable of maintaining stable data acquisition without experiencing hanging or crashing phenomena. The physical temperature measurements on the ESP32 chip surface after continuous operation showed that the device temperature remained within the normal operating range. These results demonstrate that the 5 V power supply scheme through the micro-USB interface was capable of providing a constant current supply without triggering excessive heat (overheating).

3.6. Discussion

The implementation of the IoT-based temperature and humidity monitoring system effectively addresses the limitations of conventional monitoring in the calibration laboratory. The system achieved a 100% functionality rate and maintained synchronized data across three interfaces: OLED display, local storage, and cloud dashboard. This demonstrates the feasibility of the ESP32-DHT11 architecture for continuous environmental data acquisition and supports the requirements of Clauses 6.3 and 7.5 of ISO/IEC 17025:2017. By replacing manual thrice-daily recording, the system reduces the risk of transcription errors and captures environmental fluctuations between recording intervals.

The main advantage of the proposed system is its dual-logging mechanism. The Micro SD Card records data in CSV format every 5 minutes, while ThingSpeak receives data every 1 minute, providing local backup when wireless connectivity is disrupted. The measured average packet loss of 12.39% further highlights the importance of local storage for maintaining continuous records. The CSV format also facilitates historical data processing, while the RTC provides precise timestamps for recorded measurements.

The system also demonstrated stable operation during the 24-hour stress test without overheating or logical failures. However, the DHT11 has lower accuracy and resolution than industrial-grade sensors such as the DHT22 or SHT31. Therefore, future development should consider higher-performance sensors for calibration laboratory applications requiring stricter metrological accuracy. Overall, the prototype demonstrates that dual-storage IoT monitoring can provide a practical and scalable approach to improving environmental monitoring and technical record management in calibration laboratories.

4. CONCLUSION

The design and implementation of an automatic, IoT-based temperature and humidity monitoring system have been successfully realized and validated within a calibration laboratory environment. Utilizing an ESP32 microcontroller and a DHT11 sensor, the standalone system demonstrated high reliability and performance, effectively replacing error-prone manual recording methods with continuous, automated environmental data acquisition. A key achievement of this study is the successful implementation of a dual-logging mechanism that guarantees the integrity and continuity of technical records. The ThingSpeak cloud platform provides efficient, real-time remote visualization of environmental trends, while the Micro SD Card module serves as a highly reliable local failsafe. This offline logging capability prevents data loss during network fluctuations,

ensuring uninterrupted monitoring. Furthermore, the generation of structured CSV data files offers significant practical value for laboratory management, directly facilitating regulatory compliance with Clauses 6.3 and 7.5 of the ISO/IEC 17025:2017 standard by providing accurate, historical fluctuation data essential for measurement uncertainty evaluations. Ultimately, this system proves to be a scalable, cost-effective, and robust solution for modernizing laboratory environmental monitoring. It significantly enhances operational oversight, minimizes the risk of human error, and strengthens overall quality assurance protocols in calibration facilities.

DECLARATIONS

Author Contributions:

Ryan Franki Risdianto: Conceptualization, Methodology, Software, Writing – Original Draft.

Jendra Sesoca: Primary Supervisor.

Bayu Firmanto: Co-Supervisor.

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During manuscript preparation, the authors used Gemini solely for proofreading and language refinement. The authors reviewed and validated the manuscript and assume full responsibility for its content.

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