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Implementation of the Internet of Things for Real-Time Monitoring and Control of Environmental Conditions

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Abstract

The development of the Internet of Things (IoT) enables environmental conditions to be monitored and controlled in real time through the integration of sensors, microcontrollers, wireless communication, monitoring interfaces, and actuators. This study aims to implement an IoT-based system for real-time environmental monitoring and automatic control based on measured environmental conditions, particularly temperature and humidity. The developed system integrates DHT11, MQ-2, and MQ-6 sensors with Arduino Uno R3, NodeMCU ESP8266, wireless communication, a monitoring dashboard, and relay-controlled actuators. Sensor measurements are processed and transmitted to the monitoring system, while predefined temperature thresholds are used to determine actuator activation. Experimental evaluation was conducted through sensor accuracy, communication reliability, monitoring, and automatic control tests. The results showed average temperature and humidity measurement errors of 0.78% and 1.46%, respectively, indicating relatively small deviations from reference measurements under the tested conditions. Communication testing achieved a 100% success rate for 100 transmitted packets with no packet loss, while the average communication delay was 412 ms. Automatic control testing achieved 100% success across 10 trials using a 30 °C temperature threshold. These findings demonstrate that the integrated IoT architecture can support responsive environmental monitoring and automated control within the tested operating conditions.

Keywords: *Internet of Things, Environmental Monitoring, Real-Time Monitoring, Temperature and Humidity, Automatic Control.*

INTRODUCTION

Environmental condition monitoring has become an increasingly important component of intelligent engineering as industrial automation, precision agriculture, climate research, smart buildings, and controlled environments demand continuous access to accurate and context-specific environmental data. Parameters such as temperature, humidity, air quality, and gas concentration provide critical information for identifying environmental changes and supporting timely operational decisions. Recent developments in Internet of Things (IoT) technologies have shifted environmental monitoring from periodic measurement toward interconnected sensing architectures capable of collecting, transmitting, processing, and presenting data continuously across distributed environments (Narayana et al., 2024). This transition is particularly relevant to precision agriculture, where IoT-enabled sensing enables environmental conditions to be observed at a finer spatial and temporal resolution than conventional monitoring approaches (Abu et al., 2022). Wireless sensor networks and IoT architectures have also demonstrated their potential to integrate environmental sensing with remote access, allowing users to observe changing conditions without being physically present at the monitoring location (Bandara et al., 2020). The increasing availability of low-cost microcontrollers, wireless communication modules, cloud platforms, and digital dashboards has consequently made real-time environmental monitoring more accessible for both experimental and practical applications. Yet, the value of such systems depends not only on their ability to generate real-time measurements but also on their capacity to translate those measurements into timely and reliable control actions.

Previous research demonstrates that IoT-based environmental monitoring has progressed from simple data acquisition toward integrated monitoring and control architectures, although the level of integration varies substantially across application domains. Studies of smart agriculture indicate that

IoT technologies can connect environmental sensors, communication networks, and control mechanisms to improve agricultural efficiency by enabling more responsive management of environmental conditions (Rehman et al., 2022). In smart greenhouse applications, IoT architectures have similarly been positioned as a technological foundation for Industry 4.0 because environmental variables can be continuously monitored while actuators respond to predefined operating conditions (Bersani et al., 2022). These developments suggest that IoT is not merely a communication technology for transferring sensor measurements but an infrastructure for linking physical environmental states with computational decision-making and automated responses. At the device level, an IoT-based air-conditioner monitoring prototype using NodeMCU ESP8266, DHT11, and relay modules demonstrates how temperature measurements can be connected directly to remote monitoring and appliance control (Innaya et al., 2025). Room-condition monitoring has likewise shown that platforms such as ThingSpeak can facilitate real-time visualization of temperature and humidity data, extending conventional sensor systems toward remotely accessible monitoring environments (Razali et al., 2020). The convergence of sensing, communication, visualization, and actuation therefore provides a strong technological basis for developing environmental monitoring systems that move beyond observation toward responsive control.

The breadth of measurable environmental parameters has also expanded as researchers increasingly combine multiple sensors within a single IoT architecture, particularly in applications where environmental risks cannot be adequately represented by one variable. A systematic review of IoT-based air-pollution monitoring indicates that interconnected sensing systems are increasingly employed to monitor indoor and outdoor pollutants while supporting more distributed and continuous approaches to environmental assessment (Alsamrai et al., 2024). Experimental systems combining MQ-series gas sensors with DHT11 sensors further demonstrate that gas concentration, temperature, and humidity can be acquired through a common monitoring architecture and transmitted remotely for real-time observation (Iqbal et al., 2025). Such multi-parameter configurations are important because environmental variables are often interdependent, meaning that changes in temperature or humidity can provide contextual information for interpreting other environmental conditions. IoT-based environmental information systems have similarly demonstrated the feasibility of presenting air-condition data through digital interfaces, reinforcing the role of real-time visualization in making sensor outputs operationally useful (Dewangga et al., 2024). Research on gas-leakage detection also illustrates the practical extension from sensing toward automatic responses, in which threshold violations can trigger devices such as fans, LEDs, or buzzers (Marsus Pandega & Marcos, 2023). These findings collectively indicate that environmental IoT systems can support both situational awareness and automated intervention, but they also reveal considerable variation in sensing configurations, communication mechanisms, control logic, and system architectures across studies.

Despite these advances, the existing literature remains fragmented across application-specific systems, individual environmental parameters, and heterogeneous technological architectures, creating a conceptual gap concerning how monitoring and control functions can be coherently integrated within a general-purpose real-time environmental IoT framework. Temperature and humidity monitoring using Raspberry Pi and RS232-based communication demonstrates the feasibility of continuous environmental data acquisition, while the use of LPWAN technologies illustrates how communication architecture can be adapted to support longer-range and low-power monitoring requirements (Rajkumar, 2025; Danladi & Baykara, 2022). However, many existing studies emphasize the successful acquisition or visualization of measurements without examining the complete chain from environmental sensing to data transmission, interpretation, and immediate actuation within a unified system. Research on IoT systems testing further indicates that the diversity of IoT architectures introduces challenges related to testing objectives, approaches, tools, and system reliability, suggesting that functional integration alone does not guarantee dependable system performance (Minani et al., 2024). Agricultural IoT research similarly shows that technological implementation is strongly shaped by application-specific requirements, making it difficult to generalize isolated monitoring configurations across different environmental contexts (Duguma & Bai, 2024). The literature consequently provides substantial evidence for the feasibility of individual components but comparatively less clarity regarding a compact architecture that simultaneously supports real-time environmental monitoring and responsive device control. This limitation becomes particularly relevant when the system is expected to operate continuously, because delayed communication, disconnected monitoring and actuation processes, or poorly coordinated thresholds can reduce the practical value of real-time environmental information.

The unresolved integration problem has both scientific and practical significance because environmental monitoring systems are increasingly expected to function as intelligent engineering infrastructures rather than passive measurement devices. A system that only records environmental conditions can provide historical information, but it may remain insufficient when environmental changes require immediate intervention to maintain operational stability, safety, or comfort. In smart agriculture, for instance, the effectiveness of IoT depends partly on the ability to connect environmental information with management actions that improve resource use and production efficiency (Zhang et al., 2025). Similar requirements arise in industrial and indoor environments, where temperature and humidity fluctuations may affect equipment operation, storage conditions, human comfort, or the stability of controlled spaces. Recent research on IoT-enabled sensor networks emphasizes the potential of real-time insights to strengthen process control by transforming continuously acquired sensor information into actionable operational decisions (Pandey et al., 2025). The engineering challenge is therefore not simply to increase the quantity of environmental data but to establish an architecture in which sensing, communication, processing, visualization, and actuation operate as interconnected components of one responsive system. Addressing this challenge can contribute to a more coherent understanding of how IoT technologies translate real-time environmental information into practical control mechanisms while also providing a reproducible foundation for further system development. The research position adopted here is consequently situated at the intersection of IoT-based sensing, real-time data communication, environmental monitoring, and automated control, with emphasis on functional integration rather than on a single application-specific parameter.

Against this background, this study aims to implement an Internet of Things system for real-time monitoring and control of environmental conditions by integrating environmental sensors as data-acquisition components, a microcontroller as the processing and communication unit, a network as the data-transmission medium, and control devices as responsive actuators. The system is designed to establish a continuous relationship between measured environmental conditions and corresponding control responses, enabling users to obtain real-time information while supporting remote intervention when predefined environmental conditions are reached. The study contributes theoretically by positioning IoT-based environmental monitoring as an integrated sensing–communication–control framework rather than solely as a mechanism for remote data collection. Methodologically, it contributes an implementable system architecture that connects data acquisition, transmission, visualization, threshold-based decision-making, and actuation within a single operational workflow. This approach also provides a basis for evaluating how individual IoT components function collectively in supporting responsive environmental management. The resulting framework is intended to demonstrate how real-time environmental data can be transformed into timely control actions through an integrated intelligent engineering system.

RESEARCH METHODS

This study employed an empirical system development approach involving the design, implementation, integration, and experimental testing of an Internet of Things (IoT) system for real-time environmental monitoring and control. The system integrated environmental sensors, microcontrollers, wireless communication, actuators, a server, and a monitoring dashboard to establish a continuous data acquisition and control process, following the architecture commonly applied in IoT-based environmental monitoring systems (Rajkumar, 2025). The hardware and software components used in the research are presented in Table 1, which specifies the function of each component required to reproduce the proposed system.

Table 1. Materials and Devices Used in the Research

No.	Component	Function
1	NodeMCU ESP8266	Sensor data processing and network connectivity
2	DHT11 Sensor	Temperature and humidity measurement
3	MQ-2 Sensor	Gas detection
4	MQ-6 Sensor	Methane/gas detection

5	Relay Module	Electrical device/actuator control
6	Fan	Actuator for environmental response
7	LED	System condition indicator
8	Buzzer	Warning when conditions exceed thresholds
9	nRF24L01+ Module	Wireless communication/data transmission
10	Arduino Uno R3	Sensor-side data processing
11	Computer/Server	Data storage and processing
12	Monitoring Dashboard/Application	Measurement data visualization

The hardware implementation connected the DHT11, MQ-2, and MQ-6 sensors to the acquisition and processing units, while the NodeMCU ESP8266 provided network connectivity and the relay module controlled the electrical actuators, an arrangement comparable to previous IoT-based monitoring and control implementations (Innaya et al., 2025). The system architecture consisted of sensor-based data acquisition, microcontroller-based processing, wireless data transmission, server or application-based monitoring, threshold evaluation, and actuator control, as illustrated in Figure 1.

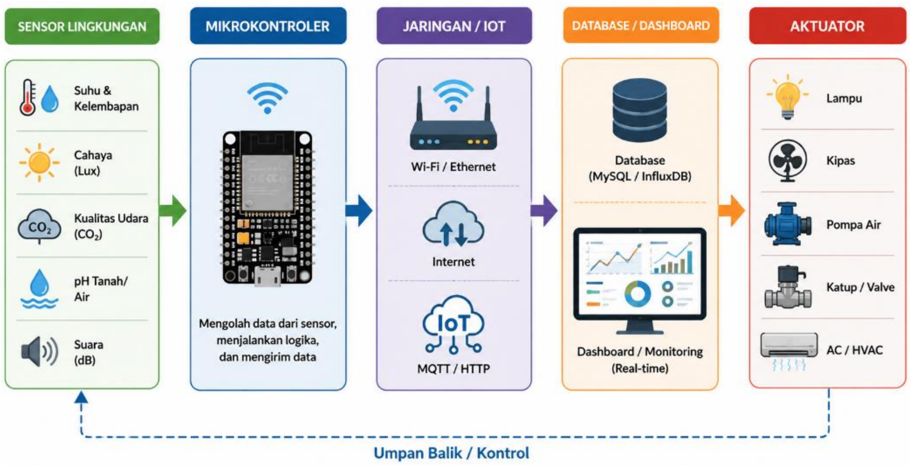

Figure 1. System Design

The software implementation comprised sensor initialization, periodic sensor reading, data processing, wireless transmission, data presentation, threshold comparison, and actuator activation, while the monitoring interface displayed current measurements and could provide historical information for observing environmental changes over time (Rizkiawan et al., 2024).

The experimental evaluation was conducted through functional and measurement tests covering sensor acquisition, communication, real-time monitoring, actuator response, and overall system operation. Sensor testing was performed by recording temperature, humidity, and gas measurements under predefined environmental conditions, while measurement validity was assessed by comparing selected sensor readings with readings obtained from an appropriate reference instrument. Communication testing evaluated the successful transmission of measurement data from the acquisition unit to the monitoring platform, whereas monitoring testing examined whether the transmitted values were displayed continuously and correctly. Actuator testing was conducted by creating conditions in which the measured parameters crossed the predefined thresholds and observing whether the relay, fan, LED, and buzzer responded according to the programmed control logic. The overall system test evaluated the complete sequence from environmental sensing and data processing to wireless transmission, dashboard visualization, threshold decision-making, and actuator execution, as represented in Figure 2.

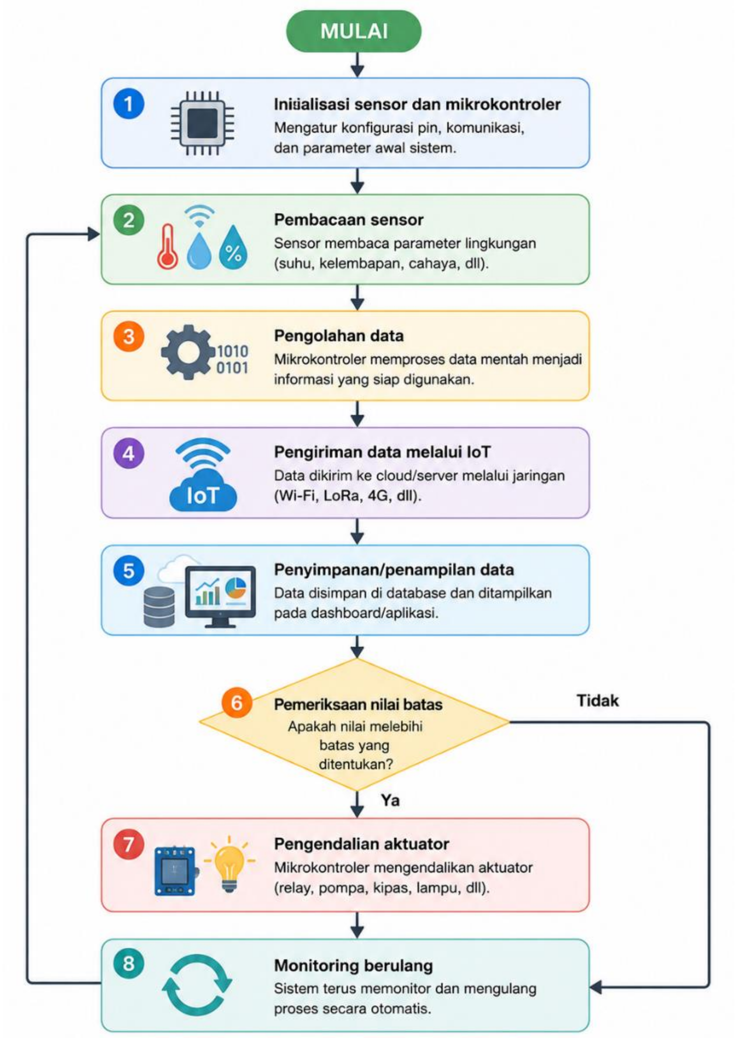

Figure 2. System Operational Mechanism

Performance was evaluated using measurement error, communication success rate, response time, and actuator execution accuracy, while the comparison with a reference measuring instrument provided an empirical basis for assessing the accuracy of the environmental sensors (Iqbal et al., 2025). This procedure enabled the study to evaluate not only whether each component operated individually but also whether the integrated IoT architecture could reliably transform real-time environmental measurements into corresponding monitoring information and control actions.

RESULTS AND DISCUSSION

System Implementation and Architecture

The implemented system integrates environmental sensors, microcontrollers, wireless communication, a monitoring dashboard, and actuators into a unified Internet of Things (IoT) architecture for real-time environmental monitoring and control. The DHT11 sensor is used to acquire temperature and humidity data, while the MQ-2 and MQ-6 sensors provide additional environmental detection capabilities, with Arduino Uno R3 and NodeMCU ESP8266 supporting data acquisition, processing, and network connectivity. This configuration establishes a continuous data flow from environmental sensing to digital processing and remote visualization, while the relay provides an interface between the controller and the physical actuator. The integration of NodeMCU ESP8266, DHT11, and relay components is consistent with previous IoT-based monitoring and control systems that connect environmental measurements with remote device operation (Innaya et al., 2025). The implemented architecture therefore extends the function of environmental monitoring from measurement acquisition toward automated response. The system is designed so that measured environmental conditions can be interpreted by the controller and subsequently used to determine the operational state of the actuator.

Figure 1 presents the system design showing the relationship between the sensing, processing, communication, monitoring, and control components. Environmental data are first collected by the sensors and transferred to the processing unit, where the measurements are read and evaluated according to the programmed system logic. The NodeMCU ESP8266 provides network connectivity for transmitting processed information to the monitoring platform, while the Arduino Uno R3 supports sensor-side data acquisition and processing. This arrangement creates a layered architecture in which sensing devices provide physical measurements, controllers perform computational functions, and the communication layer transfers information to the user interface. Similar architectures have been applied in environmental IoT systems in which sensor measurements are continuously transmitted and presented through remote monitoring platforms (Narayana et al., 2024). The dashboard functions as the information interface, allowing users to observe environmental conditions without direct access to the physical sensing equipment. The separation of these functions also provides flexibility for modifying individual components according to the requirements of different monitoring environments.

At the sensing level, the DHT11 provides the primary temperature and humidity measurements used by the monitoring and control process. The MQ-2 and MQ-6 sensors extend the system by allowing gas-related environmental conditions to be detected when required by the monitoring scenario. The use of multiple environmental sensors is consistent with IoT-based monitoring approaches that combine several parameters to obtain a broader representation of environmental conditions (Alsamrai et al., 2024). The sensor outputs are transferred to the processing unit, where the measurements are converted into data that can be transmitted and displayed through the monitoring interface. This arrangement prevents the sensing process from operating independently because each measurement becomes part of a larger data-processing and control sequence. The architecture also allows additional sensing parameters to be incorporated without changing the fundamental relationship between acquisition, processing, communication, and control. Such flexibility is relevant to intelligent engineering systems because environmental requirements may differ between indoor, industrial, agricultural, and other controlled environments.

The processing and communication components determine how the acquired measurements are transformed into information that can be accessed remotely. After initialization, the controller periodically reads the connected sensors, processes the obtained values, and prepares the data for transmission through the wireless communication infrastructure. The nRF24L01+ module supports wireless data transmission within the acquisition and communication structure, while the NodeMCU ESP8266 provides connectivity with the network-based monitoring environment. Previous research has demonstrated the use of wireless communication for transmitting temperature, humidity, and gas measurements to remote monitoring applications in real time (Iqbal et al., 2025). In the implemented system, communication is therefore positioned as an essential link between physical measurement and remote information access. Reliable data transmission is particularly important because the monitoring dashboard can only provide useful real-time information when the acquired measurements are successfully transferred from the sensing layer. The subsequent communication testing evaluates this function quantitatively through packet transmission success and communication delay.

The software implementation coordinates sensor initialization, periodic data acquisition, processing, wireless transmission, dashboard visualization, and threshold-based control within one operational sequence. The controller reads the environmental parameters and transmits the resulting measurements to the monitoring system, where current environmental conditions can be observed through the dashboard. The monitoring interface provides a means of presenting sensor information in real time and can support the observation of environmental changes over successive measurements. Similar IoT monitoring systems have used online platforms to display room-condition measurements and support remote observation of environmental variables (Razali et al., 2020). The control function adds a decision-making stage in which the measured temperature is compared with a predefined threshold before an actuator command is generated. When the temperature reaches or exceeds the specified threshold, the controller sends a signal through the relay to activate the fan, whereas a temperature below the threshold results in deactivation. This configuration establishes a direct relationship between environmental measurement and physical intervention, which forms the central operational characteristic of the implemented system.

The implementation results indicate that the proposed architecture successfully establishes an integrated pathway connecting environmental sensing, data processing, wireless communication, monitoring, and automated control. The architecture reflects the broader development of IoT systems toward integrated monitoring and control in which environmental information can be used directly to support operational responses (Bersani et al., 2022). The significance of the implementation lies not only in the presence of individual hardware components but in their coordinated operation within a single data and control flow. Measurement accuracy determines the reliability of the environmental information, communication performance determines whether that information reaches the monitoring interface in a timely manner, and the control mechanism determines whether the information can be converted into an appropriate physical response. These interdependent functions provide the basis for evaluating the system through sensor accuracy, communication success, response delay, and automatic control performance. The subsequent results therefore examine whether the implemented architecture can maintain reliable operation across these interconnected performance dimensions.

Environmental Sensor Measurement Performance

The sensor evaluation focused on the accuracy of temperature and humidity measurements because these parameters constituted the primary environmental inputs for the monitoring and control process. The measured values were compared with readings obtained from a reference instrument to determine the deviation generated by the DHT11 sensor under the test conditions. The average temperature measurement error was 0.78%, corresponding to an approximate deviation of 0.23 °C from the reference measurement. This relatively small deviation indicates that the sensor was able to follow changes in the reference temperature with a consistent measurement pattern during the test. The use of a reference instrument for sensor verification is consistent with environmental monitoring research in which temperature and humidity measurements are validated against a commercial digital thermo-hygrometer (Rajkumar, 2025). The observed temperature performance provides an adequate measurement basis for the threshold-based control mechanism because the actuator decision depends directly on the temperature value received by the controller. The result also indicates that the DHT11 can provide sufficiently consistent input data for the implemented IoT monitoring architecture under the tested conditions.

The temperature error becomes particularly relevant when the measurement is subsequently used as an input for automatic control. A deviation of approximately 0.23 °C indicates that the sensor output remained relatively close to the reference value, reducing the likelihood that minor measurement fluctuations would substantially alter the interpretation of the environmental condition. The result is also comparable in principle with previous IoT-based air-conditioner monitoring research that evaluated DHT11 performance through calibration and reported a calibration deviation of approximately 0.22 °C (Innaya et al., 2025). The small difference between the present measurement deviation and the reported calibration deviation suggests that the sensor can provide a stable basis for environmental threshold decisions when the operating range is appropriately defined. However, sensor accuracy should not be interpreted as an absolute property because environmental factors, sensor placement, calibration condition, and measurement duration can influence the resulting values. The present test therefore demonstrates the performance of the implemented sensor under the defined experimental conditions rather than establishing universal accuracy for all environmental settings. This distinction is important when deploying the system in environments with substantially different temperature or humidity ranges.

Humidity measurements produced an average error of 1.46%, which indicates a relatively small difference between the sensor output and the reference measurement during the evaluation. Although the humidity error was higher than the corresponding temperature error, the deviation remained sufficiently limited to allow the sensor to represent changes in environmental humidity within the tested scenario. The result supports the use of the DHT11 as a practical sensing component in a low-cost IoT architecture where temperature and humidity need to be acquired simultaneously. Temperature and humidity are commonly combined in environmental monitoring systems because their joint measurement provides more contextual information about the condition of a monitored space (Narayana et al., 2024). The relatively consistent humidity readings also contribute to the usefulness of the monitoring dashboard because variations displayed to users are more likely to represent actual environmental changes rather than substantial sensor instability. The humidity measurement was not directly used as the actuator threshold in the present control scenario, but its availability increases the informational value of the monitoring system. This distinction separates the monitoring role of the parameter from the decision-making role assigned to temperature.

The relationship between the sensor results and the control architecture indicates that measurement accuracy affects more than the quality of displayed information. Because the controller evaluates environmental measurements before generating an actuator command, an excessive measurement error could produce an incorrect control state when the actual environmental condition is close to the threshold. The measured temperature error of 0.78% therefore provides an important basis for interpreting the subsequent automatic-control result. The low deviation observed during testing indicates that the threshold mechanism received temperature values that were reasonably close to the reference condition. Multi-parameter environmental monitoring systems similarly rely on reliable sensor measurements before applying predefined conditions for automated responses (Iqbal et al., 2025). The present findings suggest that the sensing layer provided sufficiently consistent inputs for the implemented monitoring and control sequence under the experimental conditions. Further improvement could involve sensor calibration, longer observation periods, and testing across a wider range of environmental conditions to determine whether the observed accuracy remains stable.

The consolidated performance indicators are presented in Table 2, which places the sensor results alongside the communication and control measurements obtained during the same evaluation. The temperature error of 0.78% and humidity error of 1.46% represent the measurement component of system performance, whereas the remaining indicators describe the ability of the architecture to transmit and act upon the acquired information. The relatively low measurement errors are important because high communication reliability cannot compensate for inaccurate environmental data at the sensing layer. Conversely, accurate measurements have limited practical value if they cannot be transmitted to the monitoring interface or used to initiate the intended control response. This interaction reflects the interconnected nature of IoT architectures, where sensing, communication, and control functions jointly determine system effectiveness rather than operating as isolated components (Rehman et al., 2022).

Table 2. Recapitulation of Test Results

No.	Parameter	Simulation Result
1	Temperature sensor error	**0.78%**
2	Humidity sensor error	**1.46%**
3	IoT communication success	**100%**
4	Automatic control success	**100%**
5	Average communication delay	**412 ms**

Taken together, the sensor evaluation demonstrates that the implemented environmental sensing layer generated measurements with relatively small deviations from the reference values under the tested conditions. The temperature and humidity errors of 0.78% and 1.46%, respectively, indicate that the DHT11 provided sufficiently consistent measurements to support real-time environmental observation. The findings are relevant to the broader application of IoT because measurement reliability represents the first condition required for subsequent processing, transmission, and decision-making. The results also provide an empirical foundation for examining whether the system can maintain performance after the sensor data leave the acquisition layer. The following evaluation therefore focuses on communication reliability, response delay, and automatic control to determine whether the accuracy observed at the sensing layer is effectively translated into real-time system performance.

Real-Time Communication and Automatic Control Performance

The communication evaluation examined the ability of the IoT architecture to transmit sensor data from the acquisition unit to the monitoring system without loss under the defined test conditions. A total of 100 data packets were transmitted during the communication test, and all packets were successfully received by the monitoring system. The resulting communication success rate was therefore 100%, with 0% packet loss recorded during the test. Reliable data transmission is a critical component of real-time environmental monitoring because measurement information must reach the monitoring interface before it can be interpreted or used for control decisions. Previous IoT-based environmental monitoring research has demonstrated the use of wireless communication to transmit temperature, humidity, and gas measurements to remote monitoring applications, supporting continuous access to environmental information (Iqbal et al., 2025). The absence of packet loss in the present test indicates that the communication pathway operated consistently under the specified experimental conditions. This result establishes a reliable basis for evaluating the temporal responsiveness of the system through communication-delay measurements.

The communication success rate should be interpreted together with the time required for each measurement to reach the monitoring platform. The measured average communication delay was 412 ms, indicating that the transmitted data reached the monitoring system in less than one second under the tested network conditions. A short communication delay is important in environmental control applications because information that arrives too late can reduce the effectiveness of automated intervention. Real-time IoT monitoring architectures depend on the interaction between data acquisition, communication, processing, and presentation rather than on measurement frequency alone (Pandey et al., 2025). The 412 ms average delay suggests that the implemented system was capable of providing relatively rapid information transfer during the experiment. The value should, however, be regarded as a performance result specific to the tested network and system configuration. Network congestion, transmission distance, server workload, and wireless interference may produce different delay characteristics during deployment in more demanding environments.

The communication mechanism also determines whether environmental measurements remain continuously available to the user through the monitoring dashboard. Each successful transmission carries the processed sensor values from the acquisition layer toward the monitoring interface, allowing the current environmental state to be observed remotely. This operational model corresponds to IoT-based room-condition monitoring systems that transmit environmental measurements to online platforms for real-time visualization (Razali et al., 2020). In the present implementation, communication is not treated merely as a supporting function but as an integral component connecting physical measurements with digital information. The 100% packet delivery rate indicates that the monitoring interface received all test data generated by the acquisition unit. Combined with the 412 ms average delay, the result indicates that the system maintained both communication completeness and relatively rapid information delivery during the experimental scenario. These characteristics are particularly relevant when monitoring is coupled with automatic control because the controller depends on timely and successfully transmitted information.

The automatic-control evaluation used 30 °C as the predefined temperature threshold for activating the fan. When the measured temperature was equal to or higher than 30 °C, the controller generated an ON command through the relay, whereas a temperature below 30 °C generated an OFF command. Ten control trials were conducted to examine whether the physical actuator followed the decision produced by the programmed threshold logic. All ten trials produced actuator states consistent with the corresponding temperature conditions, resulting in an automatic-control success rate of 100%. Threshold-based control of environmental equipment is consistent with previous IoT monitoring systems in which sensor measurements are compared with predefined limits before actuators are activated (Iqbal et al., 2025). The result indicates that the implemented control logic successfully converted environmental measurements into physical actions without an observed decision mismatch during the test. This finding confirms that the system extends beyond passive monitoring by establishing a functional feedback relationship between environmental conditions and actuator operation.

The 100% control success rate also demonstrates the functional relationship between the sensing and actuation layers. The temperature value acquired by the DHT11 becomes the input for the threshold algorithm, while the resulting logical state is transmitted to the relay that controls the fan. This sequence creates a direct pathway from environmental measurement to physical intervention, which is a fundamental characteristic of IoT-based monitoring and control architectures. Similar integration of DHT11, NodeMCU ESP8266, and relay-based control has been implemented for automated environmental-device operation (Innaya et al., 2025). The present result indicates that no incorrect ON or OFF response occurred during the ten experimental trials. The consistency of the actuator response is particularly important because an incorrect state could undermine the practical value of otherwise accurate environmental monitoring. The result should nevertheless be interpreted within the scope of the tested threshold and operating conditions rather than as evidence that the control mechanism will maintain identical performance under every possible environmental scenario.

The combined communication and control results demonstrate that the implemented system can transfer environmental information and convert predefined environmental conditions into corresponding actuator responses within the tested operating range. The 100% communication success rate, 0% packet loss, 412 ms average delay, and 100% automatic-control success rate indicate that the principal information and control pathways operated successfully during the experiment. These results complement the sensor measurements reported in Table 2 because accurate environmental data require reliable transmission before they can support remote monitoring or automated intervention. The architecture therefore demonstrates a complete operational sequence in which sensing produces environmental information, wireless communication transfers the information, and threshold-based processing generates an actuator response. Such integration reflects the broader development of IoT systems from isolated sensing toward coordinated monitoring and control functions (Bersani et al., 2022). The next evaluation considers these indicators collectively to assess the overall performance and engineering implications of the implemented system.

Integrated System Performance and Engineering Implications

The integrated evaluation indicates that the proposed IoT architecture was able to connect environmental sensing, wireless communication, real-time monitoring, and automatic control within a continuous operational process. The sensor layer produced temperature and humidity measurements with average errors of 0.78% and 1.46%, respectively, while the communication layer achieved a 100% packet delivery rate during the defined test scenario. The control layer also produced a 100% execution success rate across ten threshold-based trials, indicating that the programmed decision logic was consistently translated into the expected actuator state. These results are consistent with the principle that IoT-based environmental systems should establish an interconnected pathway between sensing, data transmission, processing, and physical response rather than treating these functions as independent modules (Chen et al., 2022). The combined performance suggests that the system was operationally coherent because no major interruption was observed between the acquisition of environmental information and the execution of control actions. The significance of the result therefore lies in the successful coordination of multiple technical layers rather than in the performance of an individual sensor or controller.

The relationship among the measured performance indicators is particularly important for assessing the suitability of the system for real-time applications. Sensor accuracy determines the quality of the information entering the system, communication reliability determines whether that information reaches the monitoring layer, and response delay determines how quickly the information becomes available for observation or subsequent action. In the present experiment, the average communication delay of 412 ms indicates that the data transmission process required less than one second under the tested conditions. Real-time environmental monitoring research emphasizes the importance of timely sensor-data acquisition and communication because environmental information loses operational value when significant delays occur between measurement and availability (Narayana et al., 2024). The combination of low measurement error and sub-second communication delay provides a technically coherent basis for remote environmental observation. Nevertheless, real-time performance should be interpreted as a condition-dependent property because network characteristics and computational workloads can change the temporal behavior of an IoT system.

The threshold-based control mechanism further demonstrates how the proposed architecture transforms environmental information into an operational response. The predefined temperature threshold of 30 °C established a clear decision boundary between fan activation and deactivation, allowing the controller to convert a continuous environmental variable into a discrete control command. All ten experimental trials produced actuator states corresponding to the programmed threshold conditions, resulting in a 100% control execution rate. Threshold-based environmental control has also been applied in IoT systems for agricultural and environmental applications, where sensor values are used to trigger predefined physical responses (Rehman et al., 2022). The present implementation confirms that the control logic operated consistently within the tested temperature range. From an engineering perspective, this mechanism provides a relatively simple decision structure that can be implemented with limited computational resources while still supporting automated environmental intervention.

The architecture also provides opportunities for extending the system beyond the tested temperature-based control scenario. Because the hardware configuration includes DHT11, MQ-2, and MQ-6 sensors, additional environmental variables can be incorporated into the monitoring layer without requiring a fundamental redesign of the overall architecture. Multi-parameter IoT monitoring is particularly relevant when environmental conditions cannot be adequately represented by a single variable, such as in indoor air-quality applications where temperature, humidity, and gas concentration may interact (Alsamrai et al., 2024). The existing threshold mechanism could also be expanded from a single temperature condition to multiple decision rules involving different environmental parameters. Such an extension would allow the system to activate different actuators according to distinct environmental states, increasing its potential application in controlled rooms, laboratories, agricultural facilities, and other monitored environments. The modular structure of the implemented system therefore provides a technical basis for subsequent functional expansion.

Despite the favorable experimental results, several limitations need to be considered when interpreting the system performance. The 100% communication success rate was obtained from a test involving 100 transmitted packets and therefore represents the performance of the tested communication scenario rather than a guarantee of uninterrupted communication under different network conditions. Similarly, the 412 ms average delay may change when network congestion, transmission distance, interference, or server workload increases. Sensor performance was also evaluated under defined test conditions, meaning that the reported errors of 0.78% for temperature and 1.46% for humidity should not be generalized to all environmental ranges or deployment configurations. IoT testing research emphasizes the importance of evaluating system behavior across different operating conditions because component-level functionality does not necessarily represent system-level reliability under changing environments (Minani et al., 2024). These limitations identify further testing requirements, particularly long-duration monitoring, variable network conditions, broader environmental ranges, and repeated calibration.

From an intelligent engineering perspective, the experimental findings demonstrate the feasibility of combining real-time environmental monitoring with automated physical control through an IoT-based architecture. The system successfully transforms environmental conditions into digital measurements, transmits these measurements to a remote monitoring interface, evaluates a predefined threshold, and produces a corresponding actuator response. This integrated sequence reflects the progression of IoT applications toward intelligent and responsive environmental systems in which sensing infrastructure supports both situational awareness and operational intervention (Abu et al., 2022). The empirical results provide evidence that the proposed architecture can perform these functions reliably within the defined experimental scenario, while the identified limitations establish clear directions for more extensive validation. The overall performance is therefore better characterized as a successful prototype-level implementation with demonstrated functional reliability rather than as a universally validated environmental-control platform. Further development can focus on broader sensing coverage, adaptive thresholds, longer-term reliability testing, and more comprehensive network-performance evaluation to strengthen the system for practical deployment.

CONCLUSION

The implementation and experimental evaluation demonstrate that the proposed Internet of Things (IoT) system can integrate environmental data acquisition, wireless communication, real-time monitoring, and automatic actuator control within a unified architecture. The DHT11-based sensing process produced an average temperature measurement error of 0.78% and a humidity measurement error of 1.46%, indicating relatively small deviations from the reference measurements under the tested conditions. The communication evaluation achieved a 100% success rate for 100 transmitted data packets, with no packet loss observed during the experiment. The system also recorded an average communication delay of 412 ms, indicating that environmental measurements could be delivered to the monitoring interface in less than one second under the tested network conditions. For automatic control, the temperature threshold of 30 °C was successfully applied to determine the activation and deactivation of the fan, with all 10 trials producing the expected actuator response. These findings demonstrate that the proposed architecture can transform environmental measurements into remotely accessible information and corresponding physical control actions within the defined experimental scenario. The results position the implemented system as a functional IoT-based prototype for responsive environmental monitoring and control.

Future development should focus on broader experimental validation and improvements to the system's adaptability, reliability, and analytical capabilities. Sensor evaluation should be extended across wider temperature and humidity ranges using calibrated reference instruments to obtain more representative accuracy measurements. Communication performance should also be assessed under different transmission distances, network qualities, environmental conditions, and workloads to determine their effects on packet loss and communication delay. The control mechanism can be expanded from a fixed temperature threshold toward adaptive or multi-parameter decision logic incorporating humidity, gas concentration, and other relevant environmental variables. Historical data storage can be integrated to support trend visualization, environmental pattern analysis, and data-driven decision-making through the monitoring dashboard. Additional dashboard functions, including notifications, device-status indicators, historical records, and remote control, could further improve the system's operational usability. Long-duration testing is also required to evaluate sensor stability, communication continuity, energy consumption, actuator reliability, and overall system robustness before deployment in more demanding real-world environments.

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