# Development and Evaluation of an ESP32-based Temperature and Humidity Control Unit for Textile Storage

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**Abstract**: Monitoring temperature and humidity in textile storage warehouses is vital for maintaining product quality and ensuring optimal conditions. This study focuses on developing a temperature and humidity control unit using an ESP32 microcontroller, evaluating its performance through black-box testing. The ESP32-based system offers a scalable and energy-efficient solution for climate control, delivering precise environmental monitoring through integrated Wi-Fi and Bluetooth for affordable connectivity. Its advanced real-time data processing capabilities and compatibility with multiple sensors make it highly suitable for cost-effective, large-scale implementations in textile storage environments. The experimental approach involves controlling temperature and humidity as independent variables, while ensuring optimal storage as the dependent variable. The DHT21 sensor, ESP32 microcontroller, and relay are used as control variables. Software was developed in the Arduino IDE to manage temperature and humidity, and after validation, the program was uploaded to the ESP32 for black box testing. Results confirmed that the system effectively regulates these conditions,

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crucial for preserving textiles. The ESP32 efficiently serves as the control unit, and testing validated its ability to maintain desired limits. Future improvements could include wireless access for remote monitoring, enhancing flexibility and operational efficiency in environmental control for textile storage.

Keywords: Temperature and humidity control, Textile storage, ESP32 microcontroller, DHT21 sensor.

# Introduction

The textile and textile products industry is a key sector of the manufacturing industry and a significant driver of national economic development (Afifuddin et al., 2021). As a substantial contributor to the global economy, the textile industry plays a critical role in economic growth and industrial exports in many countries (Memon et al., 2020). However, the industry's environmental impact has raised concerns about its long-term viability (Fadara & Wong, 2022; Saha et al., 2024). Proper storage conditions are essential to maintaining the quality and durability of textile products. Factors such as high production costs, energy shortages, and outdated technology can indirectly affect storage practices (Memon et al., 2020). Ensuring yarn strength that meets or exceeds standards is crucial for the quality and durability of the final product (Harianto et al., 2023). Moreover, the growing focus on sustainability and the circular economy emphasizes the need for proper storage practices to extend product life and reduce waste (Saha et al., 2024).

Occupational safety and health are critical to ensuring the continued excellence of a company's workforce. In a production process involving machine tools and a large number of human resources, the risk of accidents is significant (Sugiyarto et al., 2024). Additionally, maintaining high product quality through proper storage practices can significantly improve consumer satisfaction, a key aspect of sustainable textile products (Fadara & Wong, 2022). Yarn unevenness is another critical factor in determining product quality (Harianto et al., 2023). Innovations aimed at reducing the environmental impact of the textile industry, such as improvements in waste management and pollution control from dyeing processes, further highlight the importance of proper storage (Hossain et al., 2024). Overall, proper storage conditions are crucial for maintaining product quality and supporting the industry's sustainability initiatives.

The design of temperature and humidity control units for textile storage rooms is crucial to ensure optimal conditions and prevent product damage. In the textile industry, stored products are highly susceptible to fluctuations in temperature and humidity. Excessive humidity can lead to mould growth, while insufficient humidity can cause fibre desiccation, both of which reduce textile quality. Therefore, the implementation of temperature and humidity control technologies in storage spaces is necessary (Mubarak et al., 2022). An effective temperature and humidity control system should account for factors such as ventilation, air circulation, and the use of sensors for real-time monitoring. For instance, DHT 22 sensors have been proven effective in maintaining stable storage conditions (Fauzi et al., 2023). Other studies emphasize the importance of using humidifiers to maintain the relative humidity balance within storage rooms (Sasono et al., 2022). Advanced technologies, such as Internet of Things (IoT)-based control systems, allow for automatic monitoring and regulation of temperature and humidity to ensure optimal storage conditions (Ridho & Musafa, 2022).

Monitoring temperature and humidity in textile storage warehouses is critical to preserving product quality and ensuring appropriate storage conditions. Various systems have been developed to address these needs, such as environment monitoring systems utilizing sensors and microcontrollers (Chen & Xiao, 2023), IoT-based warehouse monitoring systems with temperature and humidity sensors and RFID technology (Hao et al., 2022), and intelligent monitoring systems with dual control functions for temperature and humidity (Kumari et al., 2023). Additionally, flexible hybrid electronic systems have been specifically designed for monitoring temperature and humidity in storage containers, offering enhanced durability and resistance to environmental factors (Panahi et al., 2022). The use of conductor yarn for moisture sensing applications in textile warehouses further demonstrates the potential of innovative sensor structures for effective environmental monitoring (Yi et al., 2021). Overall, temperature and humidity monitoring in textile storage warehouses is essential for maintaining product quality, preventing damage, and ensuring compliance with industry standards.

Existing climate control systems for textile storage, including basic ventilation and automated HVAC systems, face challenges related to precision and adaptability. Basic ventilation setups often fail to accurately regulate temperature and humidity, exposing textiles to risks of degradation from excessive moisture or dryness. Although automated HVAC systems offer enhanced control, they are energy-intensive and expensive to maintain, especially in facilities that require constant environmental stability (Chen & Xiao, 2023). IoT-integrated systems provide improved monitoring capabilities, yet frequently lack the real-time adaptive controls necessary for preserving textiles sensitive to climate fluctuations (Yi et al., 2021).

Recent technological advancements have enabled the development of diverse environmental monitoring systems, particularly through the integration of ESP32 microcontrollers, valued for their efficiency and cost-effectiveness in climate control across various industries. Research underscores the ESP32's strengths in real-time monitoring, leveraging its processing capabilities and built-in Wi-Fi for precise temperature and humidity regulation. For example, Hercog et al. (2023) illustrate the adaptability and efficiency of ESP32-based IoT devices in environmental monitoring applications, establishing it as a viable, affordable option for industries requiring stringent climate control.

The ESP32-based system developed in this study addresses these limitations by offering a scalable, energy-efficient solution with high accuracy in maintaining environmental parameters. ESP32's built-in Wi-Fi and Bluetooth enable flexible, cost-effective connectivity, making it ideal for real-time monitoring in textile storage (Hercog et al., 2023). Its capacity for rapid data processing and handling of multiple sensor inputs supports advanced monitoring capabilities while remaining economical, crucial for industries that require affordable, large-scale deployments (El-Khozondar et al., 2024). This system surpasses conventional setups by delivering efficient data transmission and remote monitoring, significantly enhancing climate control in storage environments.

Research on the use of ESP32 microcontrollers for temperature and humidity control in textile storage rooms remains limited. While the use of ESP32 for climate control has attracted attention in various applications, its specific role in textile storage has not been extensively explored. Mubarakah et al. (2022) developed an ESP32-based system that effectively regulates humidity and temperature to meet health standards, presenting a promising solution for environments requiring climate control. Similarly, Sunardi et al. (2023) employed the Tsukamoto Fuzzy Inference System with ESP32 to control fan speed, enabling real-time mobile-based remote climate management. Additionally, Anggrawan et al. (2023) applied ESP32 to maintain temperature and humidity stability in swallow breeding environments, achieving high accuracy in preserving optimal conditions. Although these studies highlight the potential of ESP32 for climate control in various sectors, further research is required to investigate its application in textile storage rooms.

The use of ESP32 microcontrollers for temperature and humidity control in textile product storage rooms has the potential to enhance efficiency and reduce costs compared to conventional systems. Several studies have demonstrated the effectiveness of ESP32 in climate control applications. For instance, Mubarakah et al. (2022) developed an ESP32-based system that successfully regulates room temperature and humidity, achieving optimal air quality and health standards while minimizing energy consumption. Similarly, MacHeso et al. (2021) created a low-cost ESP32 asynchronous web server for real-time temperature and humidity monitoring, improving system efficiency with lower power consumption. Furthermore, Biswas & Iqbal (2018) demonstrated the cost-effectiveness of an ESP32-based automatic solar water pump system in controlling temperature and humidity, highlighting significant cost savings. These studies emphasize the potential of ESP32 to enhance operational efficiency and reduce expenses in textile storage environments.

The ESP32 microcontroller is highly suitable for creating temperature and humidity control units for textile product storage rooms, offering multiple advantages over traditional systems. ESP32 is a powerful and versatile microcontroller, ideal for IoT applications, including environmental monitoring and control. It features built-in Wi-Fi and Bluetooth capabilities, which makes it highly suitable for wireless communication and remote monitoring (Ansari et al., 2023). The superior processing power of ESP32, operating at speeds of up to 240 MHz compared to the 16 MHz of the Arduino UNO, allows for more complex tasks and faster data processing (Ansari et al., 2023). For temperature and humidity sensing, the DHT22 sensor is recommended due to its superior performance and accuracy compared to the DHT11 (Ansari et al., 2023). The ESP32 WROOM-32 module, a development board, simplifies the process of learning and experimenting with ESP-WROOM-32-based circuits. The ESP32 chip has several advantages over its predecessors, including higher speed, 32-bit processing, larger memory capacity, and integrated Bluetooth functionality (Prastyo, 2022). However, not all pins on the ESP32 are suitable for every project. Green-highlighted pins are generally safe to use, while yellow-highlighted pins can be used with caution, as some may exhibit unexpected behavior during the boot process. Red-highlighted pins are not recommended for input or output functions (Prastyo, 2022).

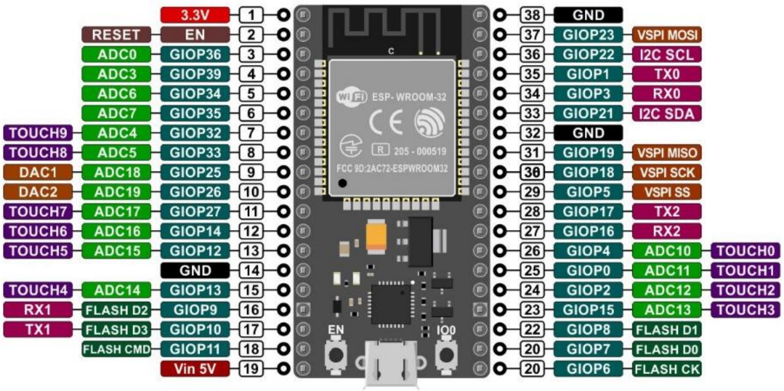


**Figure 1. Pins of the ESP32 development board** (Prastyo, 2022)

The ESP32 microcontroller can be programmed to read data from DHT22 sensors and wirelessly transmit it to cloud platforms such as Firebase for storage and analysis (Ansari et al., 2023). This configuration enables real-time monitoring of environmental conditions in storage rooms via smartphones, web applications, or other internet-connected devices (Ansari et al., 2023; Ismail et al., 2021). An interesting application of these systems is the use of predictive modelling. As demonstrated by Yuan et al. (2020), collected temperature and humidity data can be utilized with grey prediction models to forecast future environmental conditions in the storage room. This capability is particularly useful for textile storage, enabling pre-emptive actions to maintain optimal conditions. ESP32-based temperature and humidity control units for textile storage rooms offer real-time monitoring, remote access, and prediction functionalities. The system can be configured to trigger alerts or activate control mechanisms, such as HVAC systems, when temperature or humidity levels exceed predefined thresholds (Ismail et al., 2021). This ensures optimal storage conditions for textiles, potentially enhancing their quality and longevity.

The ESP32 microcontroller, similar to the ESP-12E used by Desnanjaya et al. (2023), is suitable for this application due to its wireless communication capabilities and data processing power. The system can collect temperature and humidity data using sensors like the DHT22, as demonstrated by Desnanjaya et al. (2023). These sensors have shown good accuracy, with Emge et al. (2020) reporting an average temperature error of 0.75°C and 3% humidity deviation when compared to a Thermo-Hygro measuring device. Interestingly, while most studies focus on monitoring, Huang et al. (2021) emphasized the significance of control alongside monitoring. Huang et al. (2021) introduced a PID algorithm for system correction, which can be implemented in ESP32-based systems to maintain optimal storage conditions for textiles. This approach was further supported by Desnanjaya et al. (2023), who successfully applied PID control to maintain a stable indoor temperature at 25°C. Designing a temperature and humidity control unit for a textile storage room using the ESP32 microcontroller is feasible and promising. By integrating wireless communication, accurate sensors, and control algorithms such as PID, the system can efficiently monitor and regulate the storage environment, thereby potentially improving textile durability and energy efficiency (Chen & Xiao, 2023; Desnanjaya et al., 2023).

Despite the promising features of ESP32, gaps in research persist regarding its specific application within textile storage environments. Existing solutions often lack adequate evaluation under storage-specific conditions or do not utilize optimal sensor configurations for humidity-sensitive materials like textiles. This research addresses these gaps by developing a tailored ESP32-based control unit designed to maintain the stringent environmental parameters required for textile storage, enhancing both accuracy and efficiency in maintaining climate stability.

The objective of this study is to design, develop, and test an ESP32-based temperature and humidity control system specifically for textile storage rooms. Through rigorous black-box testing, this research evaluates the system's performance, focusing on its ability to stabilize environmental conditions within the set limits. This approach provides critical insights into how ESP32 can be applied more effectively in the textile sector to ensure the longevity of stored materials. According to Narizzano et al. (2020), black box testing is a software testing method aimed at evaluating an application's functionality without accessing its source code. This method is widely used to identify errors and assess system performance based on the expected input-output behavior. For example, black box testing is applied to responsive systems whose specifications are expressed in temporal logic, enabling the detection of specification violations. Amelia Silitonga et al. (2023) says black box testing is a method used to evaluate the software interface. It is designed to identify errors and ensure that the software functions as intended. This testing approach documents the results, providing evidence of the software's compliance with the specified requirements. Moreover, black box testing has been used to validate a mobile-based agricultural application through the equivalent partitioning technique, achieving a compliance rate of 77% across 13 test cases (Sasmito & Mutasodirin, 2023). Additionally, another study demonstrated that this method could detect performance regression in large-scale software systems by employing a machine learning-based model to analyze the relationship between system performance and runtime activities (Liao et al., 2020).

In summary, this research contributes to existing knowledge by offering a practical solution that integrates modern microcontroller technology with climate control requirements in textile storage. The findings of this study aim to support the textile industry by providing a scalable, low-cost solution for climate control, potentially minimizing product degradation and enhancing operational efficiency in textile storage practices.

# Research Method

This study employs an experimental approach aimed at designing, develop and testing a temperature and humidity control unit for a textile storage room. The design uses an ESP32 microcontroller as the central control system, utilizing control algorithms based on temperature and humidity sensors. The research object is a textile storage room that requires optimal temperature and humidity conditions.

The materials and tools used include an ESP32 microcontroller, a DHT21 temperature and humidity sensor, a 5-volt power supply, Arduino IDE software for programming, jumper cables, a laptop, a USB cable to upload the program from the laptop to the ESP32 microcontroller, and a 2-output relay. To validate the DHT21 sensor readings, KAN-certified temperature and humidity measuring devices were employed.

**Figure 2. KAN-certified temperature and humidity measuring device**

Data collection was conducted on September 23, 2024, at the Akademi Komunitas Industri Tekstil dan Produk Tekstil Surakarta. Data were obtained through temperature and humidity sensor readings controlled by the ESP32, and the results were displayed on the Arduino IDE serial monitor.

This study includes three variables: the independent variable is controlled temperature and humidity; the dependent variable is the optimal condition of the textile storage room; and the control variables are the DHT21 sensor, ESP32 microcontroller, and relay. The research process consists of four stages: preparation, device design, testing and data analysis, and finally, conclusion, as illustrated in Figure 3.

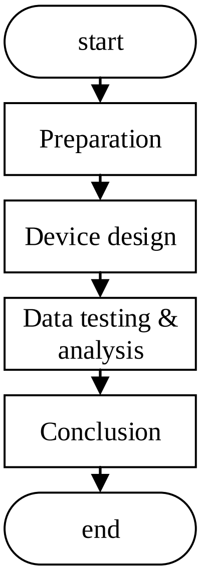


**Figure 3. Stages of research**

The preparation phase begins by gathering references and relevant literature for this research, followed by the formulation of the research problem and objectives. In the design phase, a control system is developed using the ESP32 microcontroller. The data testing and analysis section of this study comprises two main stages: testing the accuracy of the DHT21 sensor for temperature and humidity measurements, and assessing the functionality of the program using the black box testing method to ensure optimal temperature and humidity control.

First, the sensor accuracy test involved comparing the DHT21 sensor readings with those of manual instruments certified by the National Accreditation Committee (KAN). These measurements were performed in a controlled environment to verify the sensor's precision. Each reading from the DHT21 sensor was analyzed by recording its deviation from the certified instrument values, allowing the evaluation of the sensor's consistency and accuracy across different conditions.

Second, the ESP32 system function test employed the black box testing method, which evaluates the system's outputs without considering the internal program structure. The program was tested for its ability to regulate the temperature and humidity in a textile storage room, ensuring that the conditions remain within optimal limits. The test included scenarios where temperature and humidity exceeded or dropped below predefined values, aiming to verify the system's ability to respond and restore the desired conditions. The black box testing results were analyzed using key performance metrics such as response time, control accuracy, and environmental stability.

Key performance metrics used in this black-box testing include: (a) Response Time, which measures the duration required by the ESP32 system to adjust temperature and humidity levels following deviations, reflecting the control mechanisms' responsiveness; (b) Control Accuracy, assessing how precisely the system maintains environmental variables within target ranges, validating sensor readings and feedback loop effectiveness; and (c) Environmental Stability, evaluating the system's ability to sustain consistent conditions without fluctuations, essential in settings requiring steady conditions, such as textile storage.

While controlled testing environments for ESP32-based humidity and temperature systems provide consistency, they may not capture real-world variability. Controlled settings are effective for establishing baseline performance but often exclude factors like power surges and ambient fluctuations common in actual deployment scenarios (Narayana et al., 2024). For instance, research on IoT-based monitoring systems has shown that laboratory conditions support stable accuracy but may not predict challenges encountered in dynamic real-world environments (Geck et al., 2024).

Real-world testing, therefore, is advised to increase the applicability of results. Deploying the ESP32 system in variable field settings where temperature and humidity fluctuate over time would more accurately assess its responsiveness and stability under diverse conditions (Fauzi et al., 2023). Incorporating an alarm feature, as seen in IoT applications, could also provide valuable data on system adaptability and notification accuracy under different operational stresses (Mashuri & Zulfa, 2021). Together, these methods offer a thorough evaluation of the system's robustness and resilience in practical applications.

# Result and Discussion

The ESP32 is assembled with other components and connected to a 5-volt power supply. The analogue input of the ESP32 microcontroller is connected to the DHT21 temperature and humidity sensor via a 10k-ohm resistor. This resistor limits the current and ensures signal stability for humidity measurements (Yusof et al., 2019). As noted by (Wu et al., 2019), the resistor helps maintain sensor signal stability when interfacing with Arduino. In this setup, the digital pin output of the ESP32 is connected to a relay. The laptop is used to upload the program to the ESP32 microcontroller. The tool assembly schematic is illustrated in Figure 4.

After assembling the equipment, the next step is to develop programming algorithms using the Arduino IDE. Two algorithms were developed: the first tests the reading accuracy of the DHT21 sensor, and the second maintains the temperature and humidity within optimal limits. The optimal range in the textile product storage room is 55% - 65% for humidity and 27 - 33 for temperature (Hale, n.d.). These values are used as limit parameters for the program created with the Arduino IDE.

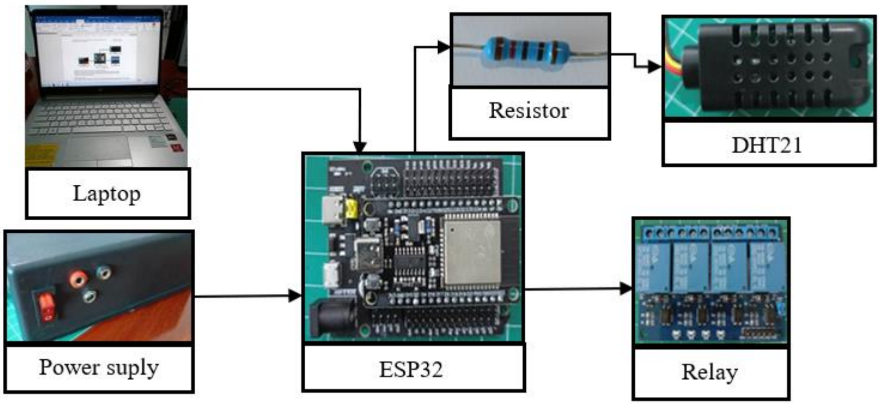


**Figure 4. Device assembly**

The algorithm for testing the temperature and humidity readings of the DHT21 sensor is illustrated in Figure 5. Any discrepancies between the DHT21 sensor readings and the results from KAN-certified temperature and humidity measuring devices are used as correction factors in the second program algorithm.

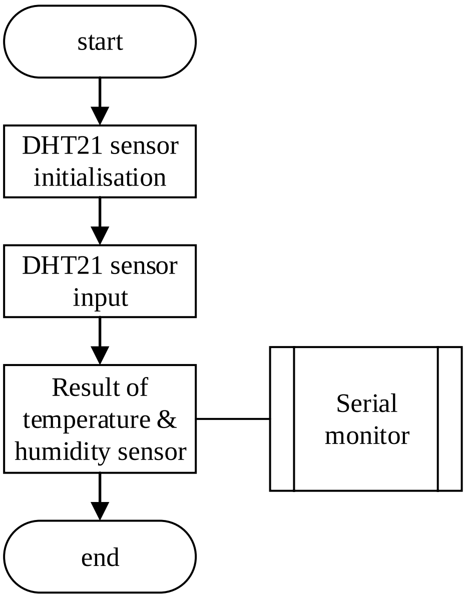


**Figure 5. DHT21 sensor testing programming algorithm**

The program was first validated using the Arduino IDE before being uploaded to the ESP32 microcontroller via a data cable. This validation is essential to identify any errors in the code. If any errors are present, the program cannot be uploaded to the ESP32 microcontroller.

After uploading the program, the DHT21 sensor detects the air temperature and humidity values, which are displayed through the Arduino IDE serial monitor. The results from the DHT21 sensor, along with the readings from the KAN-certified temperature (Temp) and humidity (Rh) measuring device, are presented in table 1.

**Table 1: DHT21 sensor reading validation**

| Number | Reading result | | | | KAN vs DHT21 gap | |
|---|---|---|---|---|---|---|
| | KAN | | DHT21 | | Temp °C | Rh % |
| | Temp °C | Rh % | Temp °C | Rh % | | |
| 1 | 24 | 49.7 | 24.3 | 55 | -0.3 | -5.3 |
| 2 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 3 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 4 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 5 | 24 | 49.7 | 24.2 | 55.1 | -0.2 | -5.4 |
| 6 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 7 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 8 | 24 | 49.7 | 24.2 | 55.1 | -0.2 | -5.4 |
| 9 | 24 | 49.7 | 24.2 | 55.1 | -0.2 | -5.4 |
| 10 | 24 | 49.7 | 24.2 | 55.1 | -0.2 | -5.4 |
| 11 | 24 | 49.7 | 24.2 | 55.1 | -0.2 | -5.4 |
| 12 | 24 | 49.7 | 24.3 | 55.1 | -0.3 | -5.4 |
| 13 | 24 | 49.7 | 24.3 | 54.9 | -0.3 | -5.2 |
| 14 | 24 | 49.7 | 24.3 | 54.9 | -0.3 | -5.2 |
| 15 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 16 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 17 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 18 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 19 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 20 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 21 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 22 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 23 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 24 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 25 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 26 | 24 | 49.7 | 24.2 | 55 | -0.2 | -5.3 |
| 27 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 28 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 29 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 30 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 31 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 32 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 33 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 34 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 35 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 36 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 37 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| 38 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 39 | 24 | 49.7 | 24.2 | 54.9 | -0.2 | -5.2 |
| 40 | 24 | 49.7 | 24.2 | 54.8 | -0.2 | -5.1 |
| **Mean** | **24** | **49.7** | **24.21** | **54.94** | **-0.21** | **-5.3** |

From the table above, it is observed that when the room temperature is set at 24°C and the humidity at 49.7%, the DHT21 sensor records an average temperature of 24.21°C and humidity of 54.94%. This discrepancy indicates that a correction factor of -0.21 for temperature and -5.3 for humidity is required. These correction factors will be applied to refine the second programme algorithm, the algorithm for maintaining optimal temperature and humidity, illustrated in Figure 6.

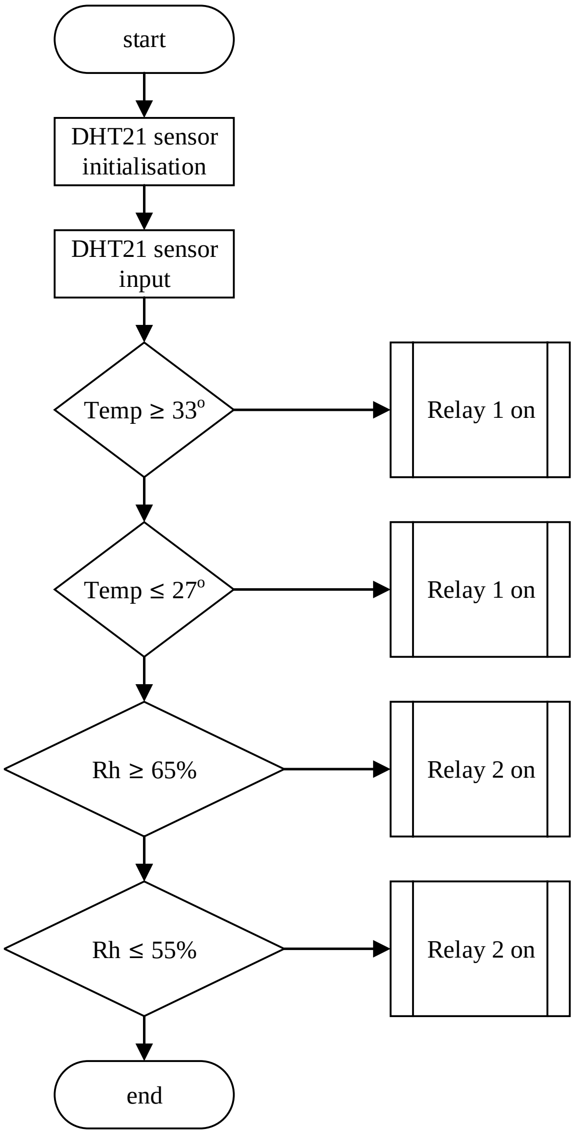


**Figure 6. The second programming algorithm**

In this system, the relay's on-off function is controlled based on the temperature and humidity readings from the DHT21 sensor. After uploading the program, the system was tested under various environmental conditions to assess the control's effectiveness. The testing was conducted using black box testing.

The testing procedure involved inputting temperature and humidity data from the DHT21 sensor, defining the expected output parameters, and observing the control unit's behavior.

Conclusions were drawn on whether the observed results matched the expected outcomes. Table 2 contains the results of testing the programme to maintain temperature and humidity at optimal limits.

**Table 2: Programme input and output testing**

| Input Data | Desired Result | Observation Result | Conclusion |
|---|---|---|---|
| Temperature and humidity values read by DHT21 sensor | Digital temperature and humidity values | DHT21 sensor readings are functioning as expected | Accepted |
| Temperature ≥ 33° | Relay 1 activated | Result as expected | Accepted |
| Temperature ≤ 27° | Relay 1 activated | Result as expected | Accepted |
| Humidity ≥ 65% | Relay 2 activated | Result as expected | Accepted |
| Humidity ≤ 55% | Relay 2 activated | Result as expected | Accepted |

During testing, the DHT21 sensor readings, displayed in the Arduino IDE serial monitor, showed that Relay 1 reliably activated when temperature values exceeded 33°C or fell below 27°C, while Relay 2 engaged when humidity levels crossed 65% or dropped below 55%. These observations align with the expected behavior of the system, validating its effectiveness for climate control in textile storage environments. If the storage temperature exceeds 33°C, textiles are prone to accelerated degradation, including color fading, fiber brittleness, and a heightened risk of microbial growth, especially when humidity levels exceed 65%. High humidity promotes the growth of mold and mildew, which severely damages fabric integrity, particularly in natural fibers like cotton and wool. Mold thrives at humidity levels above 70%, leading to stains and weakening of the fabric structure. On the other hand, when temperature falls below 27°C and relative humidity drops below 55%, the environment becomes excessively dry, increasing static electricity and brittleness in textiles, notably in cotton and wool fibers. Low humidity can also lead to shrinkage and stiffening of fibers, making textiles more vulnerable to damage during handling and reducing their longevity. Thus, maintaining a storage temperature of 27-33°C and humidity levels between 55-65% is crucial for preserving textile quality by preventing microbial growth and fiber degradation due to extreme environmental conditions.

The implementation of an ESP32-based climate control system in textile storage environments presents specific challenges that require careful consideration, especially when scaling up for larger spaces or adapting to fluctuating climate conditions. In extensive storage areas, issues such as signal strength may necessitate multiple ESP32 units or repeaters to maintain consistent coverage. Additionally, larger environments might exhibit temperature and humidity gradients, which could require deploying sensors at strategic points for accurate and uniform environmental monitoring. In climates with high variability, dynamic adjustments to fluctuating external conditions could be achieved through predictive algorithms or machine learning models.

Compared to traditional climate control systems, the ESP32 microcontroller offers distinct advantages, particularly in textile storage. Its integrated Wi-Fi and Bluetooth capabilities allow flexible, real-time data transmission without extensive wiring, which reduces installation complexity and cost. Furthermore, the ESP32's compatibility with IoT platforms enables seamless integration with cloud-based systems for remote monitoring and control—functionality that traditional systems often lack. The ESP32's low power consumption further reduces operational costs, making it especially suitable for continuous monitoring environments.

Although industrial controllers like STM32 offer higher processing power for more demanding applications, the ESP32 balances functionality and cost-effectiveness, making it ideal for medium-sized environments with budget constraints. Its open-source nature also allows for customization to meet specific storage conditions, delivering a more tailored solution than generic climate control systems.

## Conclusions

This study successfully developed a temperature and humidity control system for textile storage, utilizing an ESP32 microcontroller integrated with a DHT21 sensor and a relay system to maintain optimal environmental conditions. The system is programmed to automatically adjust the climate based on sensor readings, ensuring that storage temperatures remain between 27-33°C and humidity levels between 55-65%. This study confirms the effectiveness of an ESP32-based temperature and humidity control system for textile storage, yet several enhancements could broaden its application and precision. Implementing remote monitoring through a mobile application or web interface would enable real-time monitoring and on-the-spot adjustments to climate conditions from any location. Moreover, integrating additional sensors, such as $CO_2$ and volatile organic compounds (VOC) sensors, would optimize storage environments by monitoring air quality variables that affect textile preservation. These additions would increase the system's versatility, allowing it to meet more complex storage requirements. Future research should also explore long-term stability and efficiency in diverse textile storage settings, such as large warehouses and spaces with frequent climate fluctuations. Longitudinal studies across various real-world storage environments would reveal how the system withstands operational stresses over time, providing key insights into its durability and maintenance needs. This would be especially useful for industries with varied inventories requiring specific climate conditions. However, the current testing was limited to controlled environments, which, while establishing initial efficacy, do not fully reflect the dynamic conditions of active textile storage. Real-world testing in operational storage facilities is recommended to evaluate the system's performance amidst environmental variables like power fluctuations, human activity, and seasonal climate changes. Such testing would validate the system's robustness, flexibility, and overall practicality, providing a clearer understanding of its scalability and effectiveness in large-scale industrial applications.

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