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# Development and calibration of an Internet of Things-enabled hygrometer monitoring system for precision environmental applications

**Jelili Aremu Oyedokun[1,2*], Muniru Olajide Okelola[1], Elijah Olusayo Omidiora[3], Wasiu Babatunde Akanbi[4], and Olufemi Olayanju Awodoye[3]**

[1]Department of Electronic and Electrical Engineering, Faculty of Engineering and Technology, Ladoke Akintola University of Technology, Ogbomoso, Oyo, Nigeria

[2]Department of Engineering and Scientific Services, National Centre for Agricultural Mechanization, Ilorin, Kwara, Nigeria

[3]Department of Computer Engineering, Faculty of Engineering and Technology, Ladoke Akintola University of Technology, Ogbomoso, Nigeria

[4]Department of Crop Production and Soil Science, Faculty of Agricultural Science, Ladoke Akintola University of Technology, Ogbomoso, Nigeria

***Corresponding author:**
Jelili Aremu Oyedokun
(oyedokun.j@ncam.gov.ng)

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## Abstract

The ever-increasing need for precision, accuracy, reliability, and real-time continuous environmental measurement for agriculture, warehousing, and laboratory use has revealed shortfalls in conventional hygrometers, namely, measurement accuracy, lack of real-time remote monitoring, and insufficient data logging functionality. The main objective of this study is to create and calibrate an Internet of Things-based hygrometer system with real-time accuracy for temperature and relative humidity measurement. The proposed system comprises a DHT22 (AM2302) digital temperature and humidity sensor, an ESP32 Wi-Fi microcontroller, a local visual display using a liquid crystal display module, and a cloud interface for remote graphical and storage functionality. The system utilized C++ programming for sensing, processing, and transmitting data wirelessly. Additionally, calibration of the system was performed using three standard digital hygrometers for improved accuracy and reliability. Experimental findings showed that before calibration, Sensors A and B had a temperature difference and a humidity difference of +0.7 °C and a 1% relative humidity (RH) delay, respectively. After calibration, the sensor showed a system accuracy of ±0.2 °C and ±2–5% RH for temperature and humidity measurement, in accordance with manufacturer specifications. The system demonstrated a real-time response with update intervals of 15 seconds while maintaining stable performance for a temperature range of –40 °C to 80 °C and humidity conditions from 0% to 100% RH. Through the integration of Internet of Things connectivity with sensor calibration, the developed system enables a cost-effective, accurate, and remotely accessible solution for environmental monitoring, supporting enhanced decision-making in precision agriculture, lab monitoring, and industrial climate control.

***Keywords:*** Sensor calibration; Real-time monitoring; ESP32 microcontroller; Data logging; Precision environmental management; Wireless sensing

## 1. Introduction

Humidity is a critical constituent of the environment that plays a significant role in many natural and industrial processes within diverse fields, such as agriculture, meteorology, material science, healthcare, and manufacturing. In agriculture, humidity greatly influences plant growth, the rate of transpiration, and nutrient uptake, thereby affecting the total agricultural yield and sustainability. Meteorologically, humidity is an important factor in weather forecasting, cloud formation, and air stability. In materials science and industrial manufacturing, the level of humidity may affect the mechanical and chemical properties of materials, the durability of products, and the efficiency of processes. In healthcare environments, optimal humidity levels are critical in maintaining pharmaceutical integrity, ensuring patient comfort, and reducing the transmission of airborne diseases. Accurate, uniform, and continuous monitoring of relative humidity (RH) is crucial for maintaining optimum environmental conditions, improving product quality, and enhancing energy efficiency in systems and areas where climate control becomes important.[1]

In precision agriculture, humidity is one of the most important environmental factors affecting a vast number of physiological and agronomic processes that are critical for growth and health. It affects evapotranspiration rates directly, thereby affecting the water balance between soil and atmosphere, as well as crop transpiration, which in turn affects nutrient transfer in plant tissues. Optimal humidity enhances efficient nutrient uptake and photosynthetic efficiency, while deviations from the optimal range—whether too high or too low—can result in plant stress, nutrient deficiencies, or poor growth performance. Furthermore, humidity is an important factor influencing disease dynamics; highly humid conditions favor the proliferation of fungal and bacterial pathogens, increasing crop susceptibility to diseases.[2]

Beyond agriculture, humidity is also an important concern in industrial storage, processing, and manufacturing systems where it influences the shelf life, stability, and mechanical integrity of hygroscopic materials such as grains, pharmaceuticals, and electronic components.[3-5] Consequently, the capability to achieve precise, dependable, and timely humidity measurements has become a hallmark of contemporary automated environmental monitoring and control systems, with proper adjustment of the ambient environment on the basis of accurate and timely readings enabling ideal performance, product quality, and system efficiencies.[6-8]

The psychrometric hygrometer, which is based on the temperature difference between a wet and dry bulb thermometer to determine humidity levels, has been widely used for the measurement of RH due to its simplicity and robustness, but is often limited to manual operation and sensitive to changes in the ambient environment, such as flow rate and temperature. Resistive sensors, relying on the change in electrical resistance of hygroscopic materials as they gather or release moisture, are reasonably fast in terms of response time but suffer from issues related to poor stability due to material degradation, contamination, and temperature dependence for long-term operation.[9-11] Capacitive sensors, depending on the variation of the dielectric constant of a polymer or metal oxide film as a function of humidity, are favored owing to their minute size and ease of integration within electronic circuits. However, these devices are prone to calibration drift, nonlinear response, and signal drift over extensive operational periods, including extreme environmental conditions. Moreover, these traditional hygrometers usually measure at a single point, and thus, may not be suitable for applications that need distributed or large-scale environmental sensing, such as precision agriculture, greenhouse automation, or smart industrial systems.[12-14]

The limitation in the level of data accessibility, which relies mostly on either manual readings or simple analog output, further renders them unsuitable for use in contemporary Internet of Things (IoT) or real-time data analytics platforms. Given this context, although conventional hygrometers laid the basis for the development of humidity measurement technologies, their intrinsic limitations on accuracy, scalability, and connectivity have driven the development of novel digital and IoT-enabled humidity sensing systems, which can realize reliable, continuous, and spatially discriminated monitoring across various environmental scenarios with very high robustness.[15]

Standalone devices often provide restricted measurements, rendering them inadequate for state-of-the-art smart systems, which require continuous, networked, and adaptive environmental monitoring.[16] To overcome these challenges, IoT has emerged as a disruptive paradigm, integrating sensing devices with data gathering, wireless communication, cloud storage, and advanced analytics for real-time decision support.[17]

Recent advancements in inexpensive micro-electro-mechanical system sensors and IoT connective technologies, such as Wi-Fi, long-range, and narrowband IoT, have enabled the installation of dense networks of hygrometers capable of collecting and transmitting data in real time.[3] The commonly used digital RH sensors, such as Sensirion's SHT3x/SHT35 and Bosch's BME280/BME688 series, provide advanced linearity and temperature correction. In comparison, low-cost sensors, such as DHT11 and DHT22, although widely used, may face serious drift and reduced precision, along with shorter times of response, and thus require periodic calibration to provide satisfactory performance in precision environmental applications.[18]

Calibration is a major driver of accuracy and long-term reliability in humidity monitoring. Methods range from simple, single-point offset adjustments through multi-point calibrations utilizing saturated salt solutions or controlled humidity chambers that provide traceable RH reference values. Field-based techniques are generally performed with 33% and 75% RH reference salts to achieve two-point calibrations. Laboratory-grade systems rely on humidity generators to achieve exact sensor characterization. Besides such classic approaches, several machine learning and statistical calibration methods have recently become essential to correct for nonlinearities and temperature cross-sensitivities. Techniques such as multivariate regression, random forests, and neural networks are able to predict sensor-specific aberrations, compensate for temporal drift, and ultimately increase the sensor lifespan and system accuracy as a whole.

An IoT-enabled hygrometer system integrates multiple sub-systems, including sensors, microcontrollers (e.g., ESP32, Arduino, or Raspberry Pi), communication modules, gateways, and cloud analytics services, which enable the seamless flow of data from the sensing layer to the application layer. Furthermore, edge computing capabilities are implemented to locally perform calibration correction tasks, noise filtering, and anomaly detection before transmitting the data, thereby reducing latency and power consumption. Such intelligent systems have successfully been used in precision irrigation, climate control in greenhouses, and post-harvest storage management, where precision RH data enables automated control actions that enhance the efficiency of water use, crop production, and product preservation.

Despite the considerable development in humidity sensing and IoT-based environmental monitoring, several technical and operational hurdles continue. One of the key constraints is sensor heterogeneity: sensors, even from different manufacturers or the same batch, often differ in sensitivity, reaction time, and baseline offset. This mismatch complicates deployment at large scales and the standardization of data across networks. In addition, long-term drift due to material deterioration, age, and other environmental exposures has a significant effect on accuracy with time, which requires frequent recalibration and maintenance.

Another issue is the temperature cross-sensitivity: swings of ambient temperature may affect the humidity readings, especially in sensors where proper temperature compensation methods have not been implemented. Contamination by dust, organic vapors, or other chemical residuals further deteriorates sensor performance by altering the hygroscopic properties of sensing materials. An equally important issue is calibration traceability, which ensures that measurement results are compatible with established standards. It remains complex and costly to maintain traceability in scattered or remote sensing contexts.

System-level networked IoT deployments must also address the three key issues of communications reliability, energy efficiency, and data security. Wireless transmission may be impeded by signal interference, bandwidth constraints, or connectivity breakdowns, while battery-powered nodes operate within energy limits that restrict sensing frequency and data transmission rates. In addition, as these systems tend to operate over public or shared networks, ensuring data privacy and cybersecurity becomes paramount to prevent unauthorized access or alteration.

Therefore, a holistic system design approach is essential to address these challenges by considering long-lasting and reliable sensor hardware, intelligent self-calibration and error-correction algorithms, and efficient data collection, transmission, and processing frameworks enabled by IoT. Such a method yields not only measurement accuracy and system stability but also scalability, robustness, and sustainability, which are the mainstays of long-term deployment in precision environmental and agricultural applications.

In light of these challenges and opportunities, the present study primarily concerns the design, development, and calibration of an IoT-enabled hygrometer monitoring system for accurate environmental applications. The system aims to achieve high measurement accuracy through a multi-tier calibration procedure and to ensure reliable real-time data gathering through wireless connectivity and cloud integration. By incorporating low-cost sensors with IoT architecture and smart calibration approaches, this article offers a scalable adaptive solution for environmental monitoring that can assist in data-driven decision-making, sustainable resource management, and the enhancement of efficiency of the respective systems.

The primary aim of this study is to develop and calibrate an IoT-enabled hygrometer monitoring system capable of delivering accurate, reliable, and real-time measurements of temperature and RH for precision environmental applications. To achieve this, the study focuses on designing and implementing a low-cost IoT-based monitoring system using an ESP32 microcontroller, calibrating the developed system against standard digital hygrometers to enhance measurement accuracy and reliability, and evaluating its real-time responsiveness and suitability for remote environmental monitoring in agricultural, laboratory, and industrial environments.

Although the developed system ensures a high level of accuracy and real-time monitoring capability, it may still be affected by sensor drift over long-term operation. Therefore, future work should focus on multisensory fusion.

## 2. Materials and methods

### 2.1. Materials

The system developed herein integrates both hardware and software components that operate in harmony for efficient data collection, processing, presentation, and transfer. The software part relies on a C++ program specifically designed and developed to manage or control the operation of the system, manipulate the sensors' data, and simplify the communication between different modules. This program manages the logical flow of operations, from data collection and processing to display and cloud storage, ensuring seamless system performance.

In the hardware architecture, several key components are involved, such as the ESP32 microcontroller, DHT22 humidity and temperature sensor, liquid crystal display (LCD), switch unit, Wi-Fi module, and power supply unit. The ESP32 microcontroller serves as the central processing unit (CPU) and forms the core of the system. The ESP32 collects real-time humidity and temperature data from the DHT22 sensor, performs data processing with various algorithms, and displays the results on the LCD for rapid visualization.

The built-in Wi-Fi capability of the ESP32 allows wireless data transmission to a preselected cloud server, providing convenient options for remote monitoring and long-term data storage. The switch allows different manual functions, such as system start-up or calibration, while the power unit ensures stable and reliable operation of all components.

Overall, the integration of durable hardware components with fast, C++-based software enables real-time, accurate, and connected environmental monitoring, making the system suitable for precision applications that require durability, scalability, and ease of deployment. The C++ program developed for the system is provided in the Appendix.

### 2.2. Description of the components used

The following section provides a complete overview of all components employed in the design and implementation of the IoT-enabled hygrometer monitoring system. It identifies functional responsibilities, technical specifications, and the interrelations of hardware and software parts for accurate humidity measurement, real-time data processing, wireless transmission, and cloud-based monitoring. From the sensor and control units to display, communication, and power modules, every component is defined by its contribution to overall system performance and reliability. This comprehensive assessment clearly demonstrates how separate components combine synergistically to provide efficient and precise environmental monitoring.

#### *2.2.1. ESP32 microcontroller*

The ESP32, designed by Espressif Systems (China), is a highly capable, low-cost microcontroller built for energy-efficient applications, particularly in IoT, wearable technology, and mobile electronics. It is the follow-up to the popular ESP8266, offering greatly improved performance and functionality, including onboard Wi-Fi and Bluetooth connectivity. The ESP32 is built upon a dual-core Xtensa® LX6 CPU running at up to 240 MHz, supported by 512 KiB of random access memory, and features an ultra-low-power co-processor with 8 KiB memory optimized for low-power operation during sleep modes. This enables the ESP32 to execute high-speed tasks while maintaining power consumption for sensor hub applications.

In addition, the ESP32 includes a variety of onboard peripherals, such as analog-to-digital converters, digital-to-analog converters, universal asynchronous receiver-transmitter, serial peripheral interface, inter-integrated circuit, pulse-width modulation, and capacitive touch sensors, making it a suitable platform for developing standalone, connected devices. Its rich feature set, cost-effectiveness, and wireless capabilities make the ESP32 a reliable choice for a wide range of applications, including smart agriculture, home automation, health monitoring, and industrial control systems, where real-time communication and efficient power usage are essential, as depicted in Figure 1.

#### *2.2.2. DHT22 sensor*

The AM2302 (DHT22) printed circuit board (Shanghai, China) is a digital temperature and humidity sensor calibrated for measuring temperature and humidity levels in agricultural monitoring applications. It contains both a humidity sensor and a thermistor-based temperature sensor, combined into a single compact unit. The DHT22 operates by converting analog signals from the humidity and temperature sensors into digital data with the help of a microcontroller embedded within the sensor, ensuring accurate digital readings with minimal interference or error, as shown in Figure 2. It is widely used for IoT applications, such as monitoring greenhouse environmental conditions, storage environments, and laboratories that test crop growth.

### *2.2.3. Liquid crystal display*

The LCD is an electronic visual interface device that has been widely used to display alphanumeric characters, symbols, and simple images in embedded systems and microcontroller-based applications. In this work, an LCD module with 16 × 2 functionality (Guangzhou, China) displaying 16 characters per line over two lines was utilized

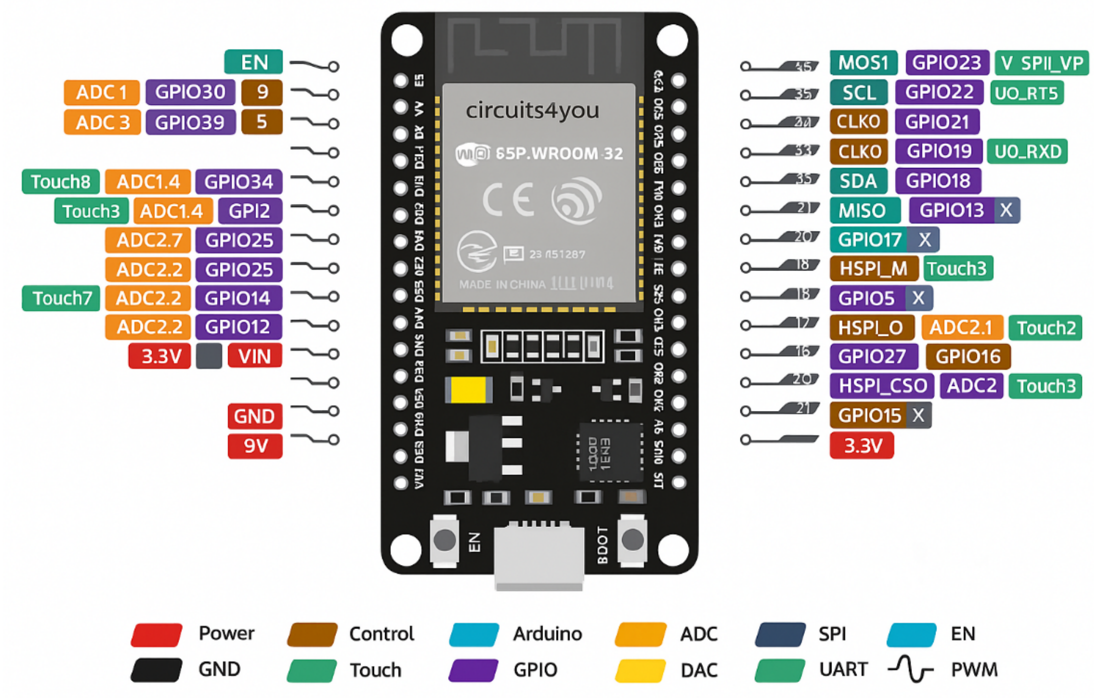


**Figure 1.** ESP32 microcontroller

Abbreviations: ADC: Analog-to-digital converter; DAC: Digital-to-analog converted; EN: Enable (chip enable/reset pin); GND: Ground; GPIO: General purpose input/output; PWM: Pulse-width modulation; SPI: Serial peripheral interface; UART: Universal asynchronous receiver-transmitter.

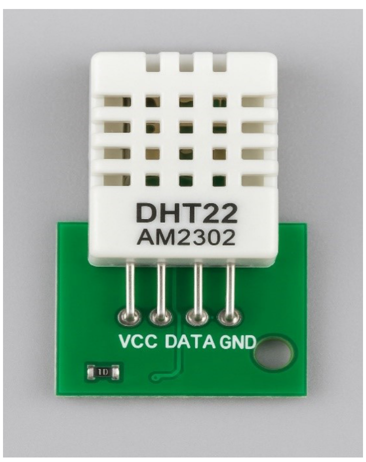


**Figure 2.** DHT22 sensor

to provide a clear, real-time display of system characteristics relating to temperature, humidity, and nutrition levels. The module operates at a standard supply voltage of 5 V direct current (DC) and is designed for low power consumption, thereby appropriate for energy efficiency and battery-powered systems.

The LCD has an integrated controller, normally the HD44780 or its equivalent, which simplifies communication and data transfer between the display and microcontroller unit. Internally, the controller provides easy interfacing via either a 4-bit or 8-bit data bus, reducing wiring complexity and conserving microcontroller input/output pins. The display operates based on light modulation by liquid crystal alignment, wherein the liquid crystal molecules change orientation under applied electric fields, modulating light passage to form letters on the screen.

The 16 × 2 LCD module is the most commonly applied in embedded system designs owing to its compactness, dependability, and relatively low cost. It can be used in environmental monitoring, control systems, or IoT-based modules. With this display capability, real-time visual feedback about system performance and environmental data can be provided for users on-site without external display devices or computers. The LCD serves as an important output interface, displaying sensor data and system status in this project; therefore, it enhances the usability and functionality of the smart monitoring system.

#### *2.2.4. Voltage regulator 7805*

The 7805 voltage regulator is a commonly used linear regulator that produces a stable and regulated 5 V DC output from a higher or fluctuating input voltage. As part of the 78xx family of fixed positive voltage regulators, the “05” designates its output capability for 5 V. It serves as a reliable power interface for low-voltage electronic systems, including microcontrollers, sensors, and digital devices requiring a steady and noise-free power supply.

In this study, the 7805 voltage regulator (Toshiba, Japan) was interfaced with a DC–DC synchronous rectification step-down (buck) converter to implement a power supply subsystem with high conversion efficiency and thermal stability. The converter efficiently reduces a variable input voltage of 5.5–32 V DC to an approximately stable 5 V level with conversion efficiencies greater than 95%, while minimizing heat dissipation through actively controlled metal-oxide-semiconductor field-effect transistor switches instead of usual diodes. The 7805 regulator then fine-tunes this voltage, providing a precisely regulated 5 V DC output at up to 1 A, ensuring dependable operation of sensitive electronic components. Its linear regulation effectively suppresses residual ripples and electrical noise from the DC–DC stage, thereby enhancing system stability, precision, and reliability.

Furthermore, the 7805 includes internal thermal overload, short-circuit, and safe-area protection features, making it robust and reliable under various operating conditions. Its simplicity, robustness, and compatibility with embedded and IoT systems make it suitable for powering smart agricultural monitoring and control applications.

Overall, the combination of the 7805 regulator and DC–DC step-down module achieves a trade-off between energy efficiency and voltage stability, providing a low-heat, high-efficiency 5 V power source that underpins the reliable operation of sensors, controllers, and communication modules in precision agricultural environments.

#### *2.2.5. 4G LTE universal mobile MiFi internet hotspot*

The 4G LTE universal mobile MiFi internet hotspot was integrated into the system to provide reliable and uninterrupted internet connectivity for the IoT-based monitoring framework. Supporting 4G LTE cellular networks, the device enables stable wireless data transmission between the DHT22 sensors and the cloud-based monitoring platform. By ensuring continuous network availability, the MiFi device facilitates real-time data acquisition, remote access, and performance monitoring throughout the study.

#### *2.2.6. Power unit*

The power unit includes two 18,650 lithium-ion batteries rated at 3,800 mAh and 3.7 V each, along with a charge controller that regulates charging for safe and efficient power management of the system. It provides a continuous power supply, enabling the use of rechargeable batteries in outdoor applications, thereby making the system suitable for deployment in rural or off-grid areas. The energy-efficient design ensures that the system can function for extended durations without frequent maintenance or battery replacement.

### 2.3. Material acquisition

The materials for the construction of the IoT-based hygrometer monitoring system were sourced locally from reputable markets in Ilorin, Kwara, Nigeria, to ensure ease of access and on-site quality inspection. Items that were not available locally were sourced online via AliExpress. The selected international orders were based on specifications, supplier ratings, reviews, and cost efficiency to meet the required research standards. This approach ensured the availability, quality, and cost-effectiveness of all materials needed.

### 2.4. Construction location

The IoT-enabled hygrometer monitoring system was developed at the Instrumentation and Control Laboratory, National Centre for Agricultural Mechanization, Ilorin, Nigeria. This location was selected due to the availability of adequate technical support infrastructure, accessibility, and a conducive research environment. These characteristics facilitated a smooth and efficient construction process, providing all necessary resources, expertise, and equipment for execution. As shown in Figure 3–6, the circuit diagram, block diagram, flow chart for construction, and flow chart for working were strictly followed.

### 2.5. Testing and calibration

The developed IoT-based hygrometer monitoring system was subjected to testing and calibration at the Instrumentation and Control Laboratory of the National Centre for Agricultural Mechanization, a facility equipped with advanced analytical instruments and specialized equipment for soil and environmental studies. To ensure high accuracy, reliability, and efficiency in monitoring ambient temperature and RH, calibration and performance assessment were conducted using three standard hygrometer meters.

During this process, the sensors and IoT components of the system underwent thorough calibration by comparing their outputs with standard reference equipment available in the laboratory to identify and adjust any discrepancies. Additionally, functional tests were conducted to assess the system's ability to transmit data in real time, integrate with IoT platforms, and respond to different environmental conditions. The results demonstrated the robustness, accuracy, and operational stability of the developed monitoring system under laboratory and simulated conditions.

### 2.6. The working principles of the developed system

The IoT hygrometer monitoring system, enabled by connected sensors, microcontrollers, communication modules, and cloud-based data management platforms, provides real-time monitoring of temperature and RH at several sites. It was fitted with two DHT22 sensors, allowing the observation of environmental parameters (temperature and RH) of two different points, such as inside and outside a greenhouse, storage facility, or room. This configuration enables effective comparison of microclimatic differences between controlled and external environments, which is essential for optimizing agricultural productivity, storage management, and environmental control.

The system was designed around an ESP32 microcontroller, which acts as the CPU or "brain" of the device, as it handles vital activities including data acquisition, signal processing, display control, and data transmission. The DHT22 sensors measure temperature and humidity, and the ESP32 converts these readings into stable digital values using filtering and calibration algorithms. The processed data is then displayed locally on a 16 × 2 LCD, offering users immediate access to environmental information in real time.

For remote monitoring, the ESP32's onboard Wi-Fi communication module transfers the processed data to a cloud-based server or IoT dashboard, from which users can explore historical trends, analyze patterns, and receive alerts from any internet-enabled device. This ensures continuous environmental monitoring even when the user is not physically present at the monitoring location.

In the power subsystem, the DC–DC step-down converter and the 7805 voltage regulator work together to deliver a stable and regulated 5 V DC supply to all components. The DC–DC step-down converter efficiently reduces input voltages in the range of 5.5–32 V to approximately 5 V with minimal heat loss, while the 7805 regulator provides accurate voltage regulation for sensitive electrical components, such as the sensors and the ESP32.

The IoT-enabled hygrometer system represents a low-cost, reliable, and energy-efficient solution for monitoring environmental parameters that are particularly important in precision agriculture, crop storage, meteorological observation, and industrial processes. By integrating sensor data collection, data processing, local display, and cloud-based communication, the system ensures accurate, continuous, and real-time monitoring of temperature and humidity conditions necessary for enhanced productivity and environmental control.

## 3. Results and discussion

The IoT-enabled hygrometer monitoring system was successfully designed and validated, as demonstrated in Figure 7. The system provided real-time measurement and monitoring of both temperature and RH. It incorporated dedicated sensors for environmental data collection, which interacted with an ESP32 microcontroller for processing and control. An LCD display provided on-site measurements, while the in-built IoT technology transmitted data to a cloud platform for remote observation and analysis. Comprehensive laboratory and field tests were conducted to assess the system's operating performance, measurement accuracy, and response to different environmental conditions.

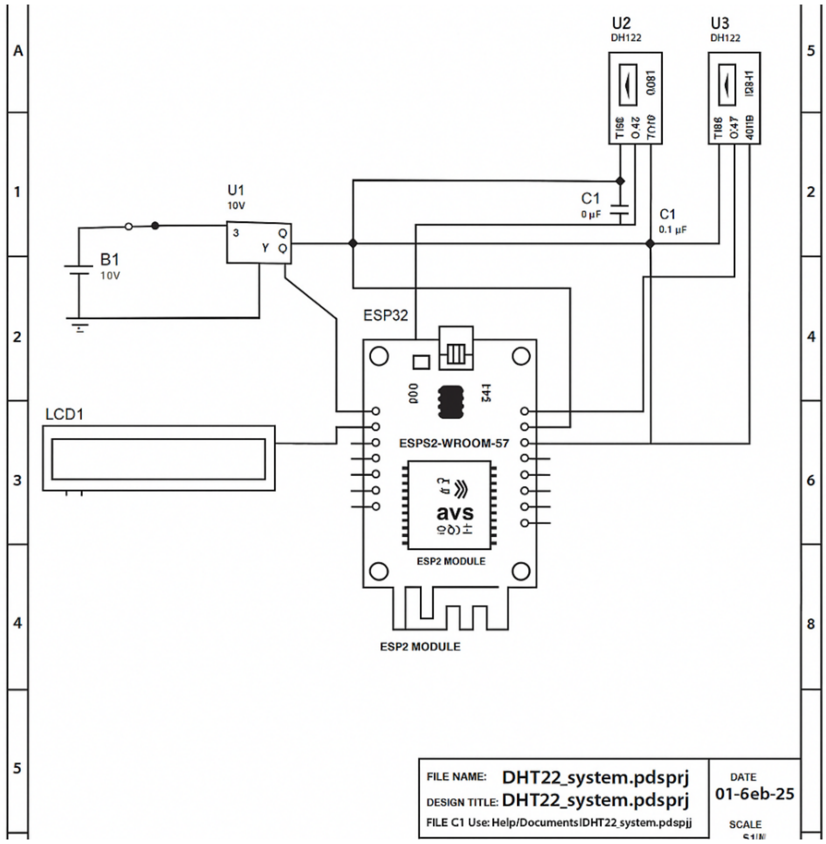


**Figure 3.** Circuit diagram of an Internet of Things–enabled monitoring system for greenhouse environments

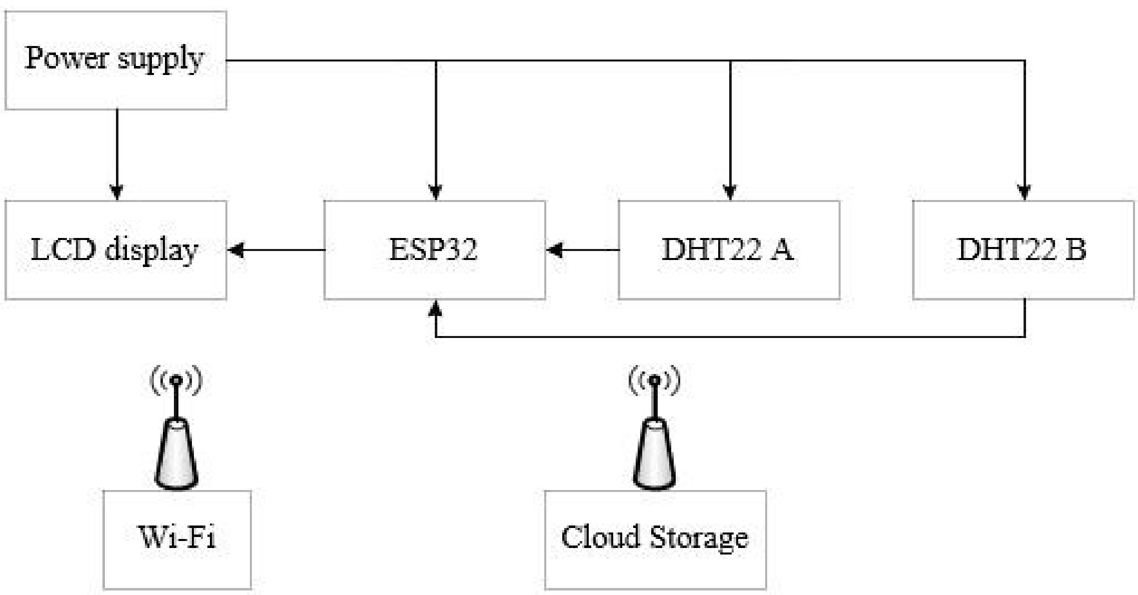


**Figure 4.** Block diagram of an Internet of Things-enabled hygrometer monitoring system

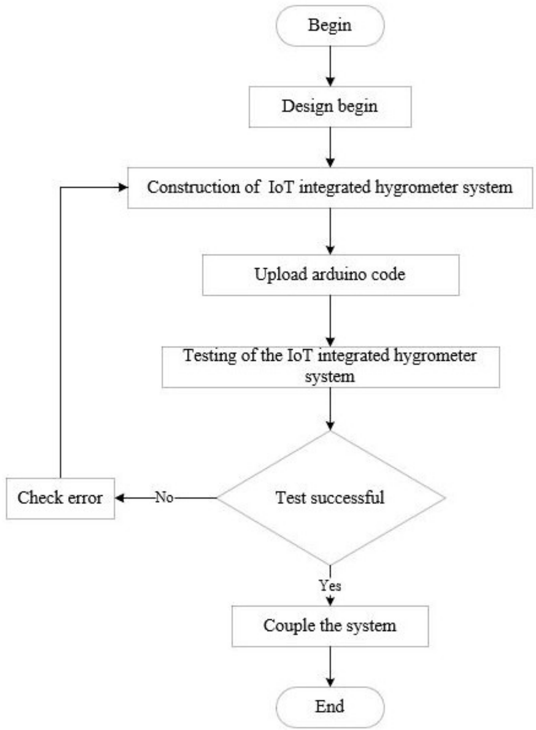


**Figure 5.** Construction flow diagram of an Internet of Things (IoT)–enabled hygrometer monitoring system for greenhouse environments

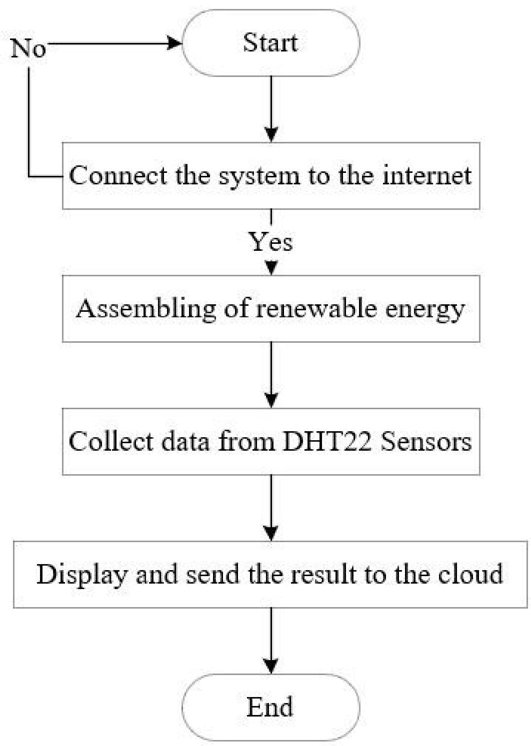


**Figure 6.** Working flow diagram of an Internet of Things–enabled hygrometer system for greenhouse environments

### 3.1. Sensor performance and accuracy

The calibration of the developed IoT-enabled hygrometer monitoring system was conducted prior to deployment to ensure measurement precision and reliability. Three commercially certified digital thermo-hygrometers were employed as reference instruments. These devices have a temperature measurement range of −10 °C to 50 °C with an accuracy of ±0.5 °C, and a relative humidity range of 10–99% RH with an accuracy of ±3% RH. The instruments are factory-calibrated and widely used for laboratory-scale environmental monitoring. Prior to calibration, a cross-verification of the reference meters was conducted to the ensure consistency and stability of baseline readings to monitor temperature and RH during the calibration procedure. The findings revealed that Sensor A recorded a temperature reading of 0.10 °C higher than the standard meter, while its RH readings matched those of the reference instrument. In contrast, Sensor B displayed identical temperature readings to the conventional meter but lagged by 1% RH in humidity measurement. These variations were adjusted through calibration adjustments to align the sensor outputs with the expected standard ranges, thereby confirming the accuracy and reliability of the calibration procedure.

During calibration, the environmental conditions were meticulously regulated using the digital hygrometers, maintaining a temperature range of –40 °C to +80 °C and an RH range of 1–100%. These stable conditions ensured consistent and reliable calibration results. The individual sensor performance was then rigorously evaluated, and the findings demonstrate that the sensors operated within their specified limits: RH range of 0–100% with an accuracy of ±2–5% RH, resolution of 0.1% RH, and repeatability of ±1% RH, as well as a temperature range of –40 °C to +80 °C with a resolution of 0.1°C and repeatability of ±0.2 °C. These findings were consistent with the manufacturer's specifications, validating the sensors' precision, stability, and suitability for accurate environmental monitoring applications.

### 3.2. System responsiveness and real-time monitoring

The system displayed effective real-time monitoring with an average data capture and processing time of less than 15 s. The ESP32's Wi-Fi module displayed sensor values on the LCD screen and communicated them to a selected email address. This approach enables remote monitoring and data logging for further analysis. Time-series plots of the transmitted data demonstrated the system's reliability and ability to capture trends in environmental parameters over different periods of irrigation and environmental changes.

### 3.3. Contribution to knowledge and practical implications

This research contributes to the existing body of knowledge by proposing an IoT-enabled hygrometer monitoring system that integrates real-time data collection, sensor calibration, and cloud accessibility within a low-cost framework. Traditional hygrometer systems, as well as many IoT-based sensor technologies that do not emphasize real-time calibration and validation, often fail to meet these requirements. In contrast, this study presents a structured model that incorporates calibration into IoT-enabled sensors for intelligent environmental monitoring applications.

From a practical standpoint, the developed system enables continuous, remote, and accurate monitoring of temperature and RH conditions, supporting informed decision-making in precision agriculture, laboratory monitoring, storage facilities, and industrial climate control management systems. Furthermore, the findings provide valuable insights into the implementation and adaptation of IoT-based environmental monitoring systems and the performance characteristics of the sensors employed, which may inform future developments and applications.

### 3.4. Future research directions

Future research should extend this study by deploying the proposed IoT-enabled hygrometer monitoring system in long-term field trials under harsh environmental conditions. Additional studies may investigate the effects of sensor aging and drift over extended operational periods. Moreover, integrating multiple sensors for the simultaneous measurement of additional environmental parameters, such as soil moisture, air pressure, and air quality, could enhance system adaptability and functionality. Future work may also incorporate advanced data analytics techniques for intelligent calibration, predictive analysis, and environmental forecasting to improve system performance. Research into low-power communication systems and renewable energy integration could further enhance energy efficiency. Finally, strengthening cybersecurity measures to protect transmitted data represents another important direction for future investigation.

### 3.5. Recommendations

Based on the successful design, development, and calibration of the IoT-enabled hygrometer monitoring system, future studies should focus on enhancing its functionality and implementation for broader environmental and agricultural applications. The system could be integrated with other IoT-based environmental monitoring tools,

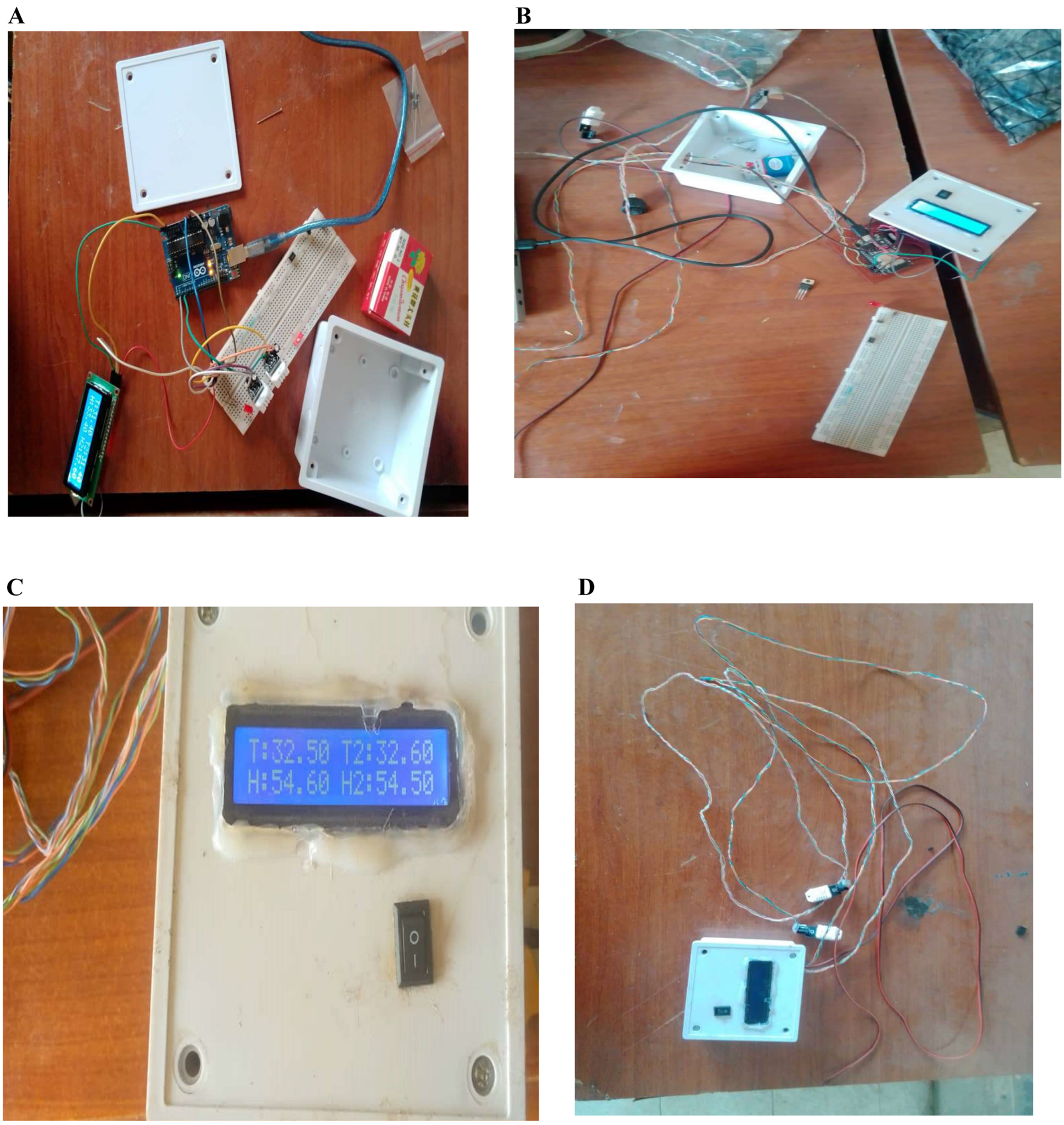


**Figure 7.** Overview of the developed system. (A) System test using Arduino Uno (construction phase), (B) system test using ESP32 (construction phase), (C) readings displayed during calibration, and (D) the developed Internet of Things–enabled hygrometer monitoring system.

such as soil moisture and air quality sensors, to form a comprehensive smart monitoring network. Incorporating data analytics and artificial intelligence algorithms will further improve predictive capabilities, enabling proactive responses to environmental variations. Additionally, establishing a user-friendly mobile or web-based interface will allow seamless visualization, data logging, and remote management, making the system more accessible to farmers, researchers, and industrial users. Long-term field validation under varied environmental conditions is also recommended to assess the stability and reliability of the system in real-world applications. Finally, collaboration with agricultural institutions and technology developers should be encouraged to support large-scale adoption and continual enhancement of the IoT-enabled hygrometer as a sustainable instrument for precise environmental control.

## 4. Conclusion

This study focused on the design and calibration of the IoT-based hygrometer system that offers accurate, reliable, and real-time readings of temperature and humidity levels for precision environmental applications. The purpose of this study was achieved through the design and calibration of a low-cost system incorporating the DHT22 sensor, ESP32 microcontroller, LCD display, and cloud platform for data visualization and interaction. The results of the calibration process confirmed a strong agreement between the developed system and the conventional hygrometer, demonstrating that the system met the stated research objectives.

The value added by this project lies in integrating sensor calibration principles with IoT-enabled remote sensing to provide a solution that is economically viable and scalable, addressing key limitations of traditional hygrometers, including the lack of continuous monitoring, extensive data logging, and remote accessibility. The study contributes to the field by proposing a structured IoT-enabled sensing framework supported by a calibration approach.

In terms of functionality, the developed system enables data-driven decision-making in agriculture, laboratory monitoring, and industrial climate control through the continuous provision of remotely accessible environmental data. The cost-effectiveness of the system enhances its suitability for deployment in environments with limited infrastructural support.

However, several limitations remain. Sensor drift may occur during prolonged operation, potentially affecting measurement accuracy, as the present evaluation was primarily laboratory-based. Future studies should evaluate long-term field deployment performance, investigate adaptive or self-calibration techniques, and explore the integration of advanced data analytics or machine learning approaches to enhance system performance. Further improvements may include the incorporation of energy-efficient strategies, hybrid sensor networks, or intelligent control mechanisms to optimize operational efficiency.

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## Conflict of interest

The authors declare they have no competing interests.

## Author contributions

*Conceptualization:* Jelili Aremu Oyedokun
*Investigation:* Wasiu Babatunde Akanbi
*Methodology:* Jelili Aremu Oyedokun, Elijah Olusayo Omidiora
*Software:* Elijah Olusayo Omidiora
*Supervision:* Muniru Olajide Okelola, Elijah Olusayo Omidiora, Wasiu Babatunde Akanbi
*Validation:* Olufemi Olayanju Awodoye
*Writing–original draft:* Jelili Aremu Oyedokun
*Writing–review & editing:* Muniru Olajide Okelola, Olufemi Olayanju Awodoye

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

Not applicable.

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## Appendix

### C++ program code

```
/*
 *A product of AGREM SYSTEM designed to measure the atmospheric temperature and relative humidity of two different
 *environments simultaneously.
 *This system uploads the values to an email account.
 *DECEMBER 9TH, 2024.
 */
//#include "AGREMSYSTEM"
#include "Arduino.h"
#include <EMailSender.h>
#include <WiFi.h>

#include <SimpleDHT.h>
#include <LiquidCrystal_I2C.h>

LiquidCrystal_I2C lcd(0x3F,16,2); // set the LCD address to 0x27 for a 16 chars and 2 line display

int pinDHT22 = 18;
int pinDHT23 = 19;
SimpleDHT22 dht22(pinDHT22);
SimpleDHT22 dht23(pinDHT23);

String parameters;

const char* ssid = "OYEDOKUN";
const char* password = "abimbola1@1986";

unsigned long previousMillis = 0;       // will store last time mail was updated

// constants won't change:
const long interval = 10800000; // every 3 hrs
//const long interval = 900000; // every 15 minutes
//const long interval = 60000; // every 1 minute

```

```
uint8_t connection_state = 0;
uint16_t reconnect_interval = 10000;

EMailSender emailSend(“onlinemonitoringsystem01@gmail.com”, “vcwfpxwzrvrjvpql”, “emailfrom@gmail.com”, “AMBIANCE-RECORD”);

uint8_t WiFiConnect(const char* nSSID = nullptr, const char* nPassword = nullptr)
{
  static uint16_t attempt = 0;
  Serial.print(“Connecting to “);
  if(nSSID) {
    WiFi.begin(nSSID, nPassword);
    Serial.println(nSSID);
  }

  uint8_t i = 0;
  while(WiFi.status()!= WL_CONNECTED && i++ < 50)
  {
    delay(200);
    Serial.print(“.”);
  }
  ++attempt;
  Serial.println(“”);
  if(i == 51) {
    Serial.print(“Connection: TIMEOUT on attempt: “);
    Serial.println(attempt);
    if(attempt % 2 == 0)
      Serial.println(“Check if access point available or SSID and Password\r\n”);
    return false;
  }
  Serial.println(“Connection: ESTABLISHED”);
  Serial.print(“Got IP address: “);
  Serial.println(WiFi.localIP());
  return true;
}

void Awaits()
```

```
{
  uint32_t ts = millis();
  while(!connection_state)
  {
    delay(50);
    if(millis() > (ts + reconnect_interval) && !connection_state){
      connection_state = WiFiConnect();
      ts = millis();
    }
  }
}

void setup()
{
  Serial.begin(115200);
 // initialize the lcd
 lcd.init();
 // Print a message to the LCD.
 lcd.backlight();

  connection_state = WiFiConnect(ssid, password);
  if(!connection_state)  // if not connected to WIFI
    Awaits();         // constantly trying to connect

  EMailSender::EMailMessage message;
  message.subject = “DHT22 READINGS”;
  message.message = “”;

  EMailSender::Response resp = emailSend.send(“soil.status.update@gmail.com”, message);

  Serial.println(“Sending status: “);

  Serial.println(resp.status);
  Serial.println(resp.code);
  Serial.println(resp.desc);
  lcd.print(“CONNECTED”);
  delay(1000);
```

```
}

void loop() {

  // start working...
  Serial.println(“=================================”);
  Serial.println(“Sample DHT22...”);

  // read without samples.
  // @remark We use read2 to get a float data, such as 10.1*C
  //    if user doesn’t care about the accurate data, use read to get a byte data, such as 10*C.
  float temperature = 0;
  float humidity = 0;

  int err = SimpleDHTErrSuccess;

  if ((err = dht22.read2(&temperature, &humidity, NULL)) != SimpleDHTErrSuccess) {
    Serial.print(“Read DHT22 failed, err=”); Serial.print(SimpleDHTErrCode(err));
    Serial.print(“”); Serial.println(SimpleDHTErrDuration(err));
    Serial.print(“  Sensor One disconnected”);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(“Sensor”);
    lcd.setCursor(7,0);
    lcd.print(“One”);
    lcd.setCursor(0,1);
    lcd.print(“Disconnected”);
//    lcd.clear();
    delay(2000);
    return;
  }

  float temperature3 = 0;
  float humidity3 = 0;

// int err = SimpleDHTErrSuccess;
  if ((err = dht23.read2(&temperature3, &humidity3, NULL)) != SimpleDHTErrSuccess) {
```

```
    Serial.print(“Read DHT23 failed, err=”); Serial.print(SimpleDHTErrCode(err));
    Serial.print(“,”); Serial.println(SimpleDHTErrDuration(err));
    Serial.print(“  Sensor two disconnected”);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(“Sensor”);
    lcd.setCursor(7,0);
    lcd.print(“Two”);
    lcd.setCursor(0,1);
    lcd.print(“Disconnected”);
   // lcd.clear();
    delay(2000);
    return;
   }

     if (((err = dht23.read2(&temperature3, &humidity3, NULL)) != SimpleDHTErrSuccess)&&((err = dht22.read2(&temperature, &humidity, NULL)) != SimpleDHTErrSuccess))
    {
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(“Sensors”);
    lcd.setCursor(0,1);
    lcd.print(“Disconnected”);
    }

   Serial.print(“Sample OK: “);  Serial.print((float)temperature); Serial.print(“ *C, “);
   Serial.print((float)humidity); Serial.println(“ RH%”);

   Serial.print(“Sample OK: “);
   Serial.print((float)temperature3); Serial.print(“ *C, “);
   Serial.print((float)humidity3); Serial.println(“ RH%”);

  parameters = (String(“Internal temperature: “)+ String((float)temperature)+ String(“ *C, “)+ String(“Internal humidity: “)
  + String((float)humidity)+ String(“ RH%, “)+ String(“External temperature: “)+ String((float)temperature3)+ String(“ *C, “)
  + String(“External humidity: “)+ String((float)humidity3)+ String(“ RH%.”));

```

```
 lcd.setCursor(7,0);
 lcd.print(" ");
 lcd.setCursor(7,1);
 lcd.print(" ");
//External DHT
 lcd.setCursor(0,0);
 lcd.print("T:");
 lcd.setCursor(2,0);
 lcd.print((float)temperature);
 lcd.setCursor(0,1);
 lcd.print("H:");
//   float humidity2 = (humidity * 0.9341) + 22.319;   // Calibration
 lcd.setCursor(2,1);
// lcd.print((float)humidity2);
 lcd.print((float)humidity);

//Internal DHT
 lcd.setCursor(8,0);
 lcd.print("T2:");
 lcd.setCursor(11,0);
 lcd.print((float)temperature3);
 lcd.setCursor(8,1);
 lcd.print("H2:");
//   float humidity4 = (humidity3 * 0.9341) + 22.319;   // Calibration
 lcd.setCursor(11,1);
 lcd.print((float)humidity3);
// lcd.print((float)humidity4);

 // DHT22 sampling rate is 0.5HZ.
 delay(2000);

  unsigned long currentMillis = millis();

 if (currentMillis - previousMillis >= interval) {
  // save the last time you sent the mail
  previousMillis = currentMillis;

```

```
    connection_state = WiFiConnect(ssid, password);
    if(!connection_state)  // if not connected to WIFI
      Awaits();         // constantly trying to connect

    EMailSender::EMailMessage message;
    message.subject = ("AMBIANCE RECORD");            //The stand number from the keypad comes in here
    message.message = (parameters);

    EMailSender::Response resp = emailSend.send("soil.status.update@gmail.com", message);

    Serial.println("AGREM SYSTEM Sending status: ");

    Serial.println(resp.status);
    Serial.println(resp.code);
    Serial.println(resp.desc);
    }
    return;
   }
```