

# IoT-based monitoring system for temperature and humidity control in additive manufacturing titanium powder handling and storage

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**Abstract.** Additive manufacturing (AM) is a layer-by-layer process, of joining powder material to build solid parts from 3D model data. Titanium powders are very reactive when exposed to ambient conditions, which can result in degradation of the powder. Therefore, correct powder handling and storage play a crucial role in ensuring the required performance and part quality. This paper presents an Internet of Things (IoT)-based system designed to monitor temperature and humidity in real time, enabling detection, notification and data recording. The development of the monitoring system was accomplished based on the environmental data received during handling and storage of titanium powder from the Centre for Rapid Prototyping and Manufacturing (CRPM). The system uses four DHT22 sensors, where data is displayed on an organic light-emitting diode (OLED) screen and graphically analysed via the IoT-based ThingSpeak web platform. When the conditions exceeded the threshold, the automation tool IFTTT (If This Then That) automatically sent a notification to the user via email for further action. Temperature and humidity fluctuations were recorded and compared using graphical representations analysed from ThingSpeak and MATLAB. The system effectively detected minor environmental changes and demonstrated reliable performance in maintaining controlled conditions during powder handling and storage processes.

## 1 Introduction

Additive manufacturing (AM) of titanium alloys involves the application of a high-powered laser to melt and fuse titanium metal powder particles layer by layer to form a solid part [1]. This technique is also referred to as the direct metal laser sintering (DMLS) process where a 3D object is built from using a raw metal powder [1]. The condition of the powder and the way it has been handled or stored can directly affect the quality of the printed components. Therefore, proper handling and storage of powder are important to maintain the material's properties within the required specifications and to ensure the environment is always under

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control. Consistent monitoring and good management during powder handling and storage are key to achieving process repeatability and reliability to ensure the integrity of the final DMLS parts.

The Ti6Al4V alloy was found to be particularly prone to react with moisture and degrade when exposed to ambient conditions [2]. The powder handling process for medical implants includes the following important steps: (1) adding virgin powder into the machine to prepare for the process, (2) collecting unused powder after a build, (3) sieving and reusing the powder, and (4) properly storing the remaining powder to be used for a next cycle. During these steps, ambient conditions must stay within the acceptable ranges.

The integration of wireless communication technologies, especially those powered by the Internet of Things (IoT), has significantly advanced environmental monitoring processes in various applications [3, 4]. The IoT refers to a network of interconnected physical devices that collect, share, and exchange data in real-time without any human intervention [3, 4]. One of the most valuable applications of IoT offers cost-effective, easy-to-install and reliable systems capable of real-time monitoring without disrupting the workflow [4]. The technology enables continuous tracking of temperature and humidity, ensuring optimal conditions are maintained [4]. This application does not only enhance process reliability but also minimises human error.

## 1.1 Powder handling processes in additive manufacturing

The handling and storage of the powder in DMLS can be divided into two main processes, which are pre-processing and post-processing. The pre-processing stage involves different operations, such as vacuum cleaning the chamber after every process to remove un-melted powder from previous builds and adding virgin powder supplied directly by the manufacturer into the DMLS machine's bin (in this study an EOS M290 was used) for the next building process. Once the machine is prepared and the design file is loaded, the building phase continues. In this stage, the laser selectively melts and fuses the powder layer by layer until the part is finished. This process is largely automated and continues until the entire component is completed. Following the build, the post-processing stage begins. This stage includes different heat treatments and manually removing the printed parts from the build chamber, as well as collecting the remaining un-melted powder. The remaining un-melted powder is temporarily stored in plastic bins for a short time before undergoing a sieving process to ensure it meets the required particle size specifications for the machine and maintains the flowability that is required, when reused.

During these stages, particularly during the cleaning of the build chamber and the collection of the unused powder into temporary bins, titanium powder is slightly exposed to ambient air. As discussed in the previous section, the presence of humidity and fluctuating temperatures can negatively impact the chemical and physical integrity of the powder [2, 5, 6]. Exposure to moisture can result in oxidation and agglomeration of particles, which degrade powder flowability and compromise the overall performance of the laser powder bed fusion process [2, 5, 6].

Messe et al. [2] investigated the effect of humidity on Ti6Al4V powder over ten months at  $22 \pm 5$  °C with moisture content of 18%, 58% and 75%, while the temperature remained stable at  $22 \pm 5$  °C. They found that higher humidity and longer storage led to the formation of agglomerates, most seen after 273 days with slight surface darkening at 58% and 75% and no changes were observed at 18%. Weiss et al. [6] examined four powders exposed to 50% and 80% relative humidity and found that higher moisture caused agglomeration and affected part quality

The ambient conditions listed in Table 1 are recommended to ensure proper functioning of the AM machine, powder material and safety devices, while maintaining consistent production quality.

**Table 1:** Ambient conditions recommended in EOS M290 installation manual and ISO-ASTM 52928 [7, 9].

EOS M290 installation manual	BS EN ISO-ASTM 52928 specifications
Temperature for machine in an operating state > 20 - 25 °C Max. 55% relative atmospheric humidity	Temperature for machine in an operating state 15 - 25 °C Max. 55% relative atmospheric humidity
Temperature for sieving module in operating state 10 - 40 °C * No value given for relative atmospheric humidity	Temperature for sieving module in operating state 15 - 25 °C Max. 55% relative atmospheric humidity
Temperature for stored metal powder in non-originally sealed packed bin 15 - 25 °C Max 40% relative atmospheric humidity	Temperature for stored metal powder in non-originally sealed packed bin 15 - 25 °C Max 55% relative atmospheric humidity

EOS recommends temperature and humidity ranges as shown in Table 1 to maintain optimal performance, material integrity, and safety throughout the EOS AM processes [7]. Nikon SLM Solution Group AG [8] advises that ambient for room conditions should range between 20 °C to 25 °C with 40% to 60% relative humidity while ASTM 52928 [9] specifies 15 °C to 25 °C and 55% depending on material, process and application. For powder handling processes, temperature should remain above 15 °C and permissible relative humidity above 20%, as excessively low humidity raises the risk of generating sparks [7, 8].

## 1.2 IoT-based temperature and humidity monitoring for quality control

The use of IoT-based temperature and humidity monitoring systems has proven effective in maintaining consistent environmental conditions, thereby significantly reducing the reliance on manual checks [3, 4, 11, 12]. These smart systems can interact with other devices or platforms, enabling remote monitoring, automation, and enhanced process control. Recent studies have highlighted the increasing adoption of cloud-based IoT systems for monitoring environmental parameters in industrial applications. For instance, Seman et al. [3] developed a continuous monitoring system for atmospheric temperature and humidity in a controlled environment, demonstrating how IoT can maintain optimal conditions with minimal human intervention. Similarly, Rahman et al. [4] implemented an IoT-based platform with automated alert features, capable of notifying users about critical fluctuations across multiple monitoring points. The following subsections illustrate IoT components for data acquisition and communication.

### 1.2.1 DHT22 temperature and humidity sensor

The DHT22 digital sensor is a cost-effective device capable of accurately measuring ambient temperature from -40 °C to 80 °C with an accuracy of  $\pm 0.5$  °C and relative humidity from 0 to 100% with an accuracy of  $\pm 2\%$  at the same time [13, 14, 15]. It features four pins for connection, where pin one provides power (3.3 V, and 5 V depending on the microcontroller), pin two is a bi-directional data line that must connect to a digital GPIO (General-Purpose Inpit/Output) pin, pin three remains unconnected and pin four connects to the ground and

must be tied to the microcontroller's ground [13, 15]. This sensor is considered as one of the most accurate sensors for wide ranging temperature and humidity measurements and is widely used for environmental monitoring in different areas [13, 15].

### *1.2.2 ESP32-S2 mini microcontroller*

Microcontroller boards are designed to integrate a communication interface and peripheral components with the main processor chip [16]. The ESP32 chip, in particular, has grown significantly in recent years, supported by hardware and software advancement [16]. These boards are compatible with the Arduino Integrated Development Environment (IDE) which allows rapid development and deployment of applications [11]. Arduino-based microcontrollers are excellent to be used for any IoT application due to its flexibility, programmability and capability to interface with circuits, switches and sensors [11]. Studies highlighted its effectiveness in real-time monitoring applications [11, 16].

### *1.2.3 HW-724 ESP32 organic light-emitting diode (OLED) display module*

The organic light-emitting diode (OLED) display is used to present the temperature and humidity data collected by the DHT22 sensor. The module connects with an ESP32 microcontroller and allows real-time display of sensor data and system status directly on the device [11, 14]. Programming is done via the open-source IDE which supports multiple operating systems and provides a user-friendly interface for writing and uploading code [11, 14]. There are various IoT platforms available that can be used to support the development of IoT applications. Among them, MATLAB by MathWorks is widely utilised for IoT projects, particularly for advanced data analysis and processing [4, 11, 17].

## **1.3 Integration of cloud-based ThingSpeak**

ThingSpeak is an open-source IoT cloud-based platform that is mostly used for device-to-device communication via the internet [4, 11]. It allows devices such as sensors and microcontrollers to exchange real-time data by translating it into manageable information. Each sensor connected to the device is uniquely identified by their device ID, Application Programming Interface (API) key, and data stream name to allow secure communication [14]. Studies [11, 12] have demonstrated the effectiveness of ThingSpeak for monitoring temperature and humidity, providing real-time analysis and visualisations.

## **1.4 IFTTT trigger alert notification**

Another tool is the IFTTT (If This Then That) application, which is a web-based service that allows integration with different IoT applications. The IFTTT operates on applets, which are building blocks of automation connecting two or more devices, responding to events or triggers when conditions are not met [4, 17]. Ab Rahman et al. [4] integrated the application of IFTTT in his work to receive notifications when the data exceeded the threshold values. Anuar et al. [17] built a prototype that validated the temperature and humidity system where he included the functionality of IFTTT for notification and awareness. The notification is automatic and triggered by applet configuration via SMS, email, or a device alert.

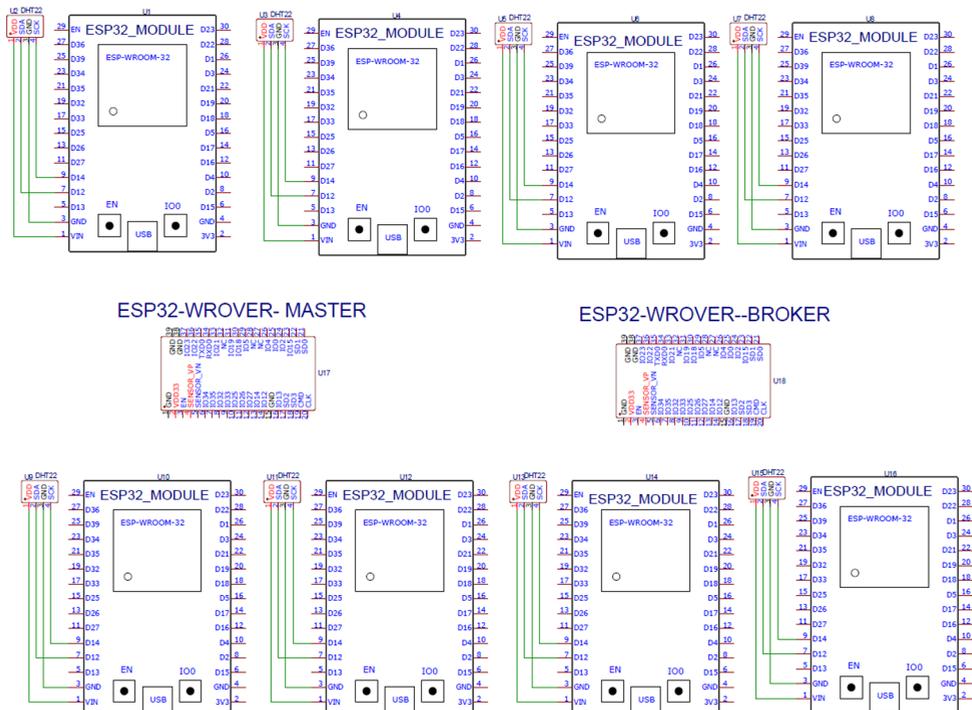
This study intends to implement IoT devices and platforms to monitor and control humidity and temperature during the powder handling processes.

## 2 Methodology

A low-cost IoT-based system was developed for real-time monitoring and control of environmental conditions during the powder handling processes. Three critical locations were monitored: (1) the handling area where powder is actively transferred or processed, (2) inside the plastic bins where powder is stored prior to sieving, and (3) within the sieving module during the sieving operation. A customised data acquisition system, consisting of humidity sensors, microcontrollers and an OLED display was integrated with a web server to enable continuous data logging and remote access.

### 2.1 The ESP32-based IoT system wiring diagram

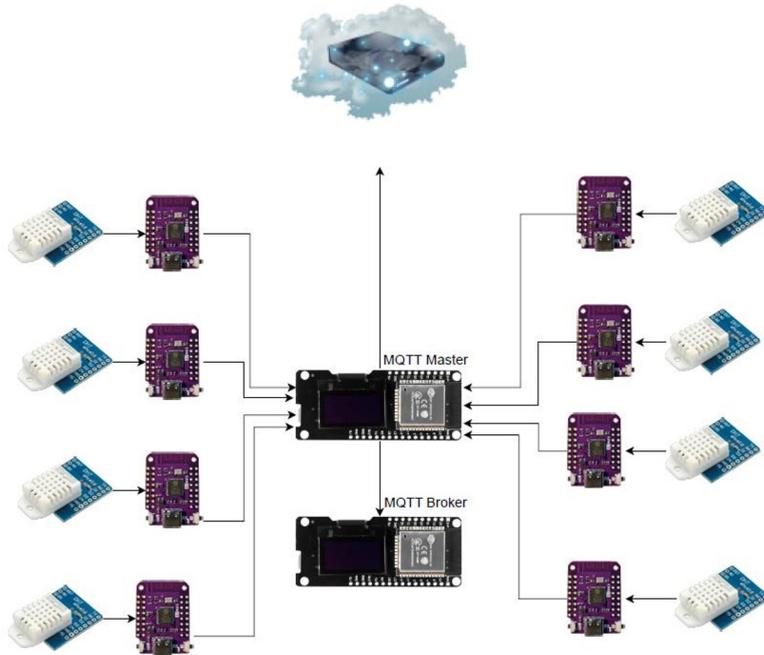
In this methodology, a wireless sensor network was created using eight DHT22 temperature and humidity sensors, each connected to its own ESP32-S2 mini microcontroller acting as a slave device. The ESP32-S2 minis were powered with 5 volts via USB cable and programmed to collect sensor data every 30 seconds. To conserve energy and reduce network traffic, the devices entered deep-sleep mode between readings. Upon waking, each device sent its data as MQTT message over Wi-Fi to a central master ESP32, which also had a built-in OLED display. The master was configured as an MQTT broker and aggregated the readings from all eight slaves, displaying them in real-time on the OLED for immediate local monitoring. The hardware wiring of sensors, broker and master device is illustrated in Figure 1.



**Fig. 1.** Wiring diagram of the ESP32-based IoT system showing eight ESP32-S2 mini slaves, one ESP32 MQTT broker and one ESP32 master device with OLED display.

Simultaneously, the master forwarded the data to the cloud-based ThingSpeak server using HTTP/MQTT enabling remote storage, visualisation and analysis. For automation

notification, the ThingSpeak server in MATLAB was configured to interface with IFTTT using HTTP requests. MATLAB monitored incoming sensor data, and when predefined thresholds were exceeded, an HTTP post request was sent from ThingSpeak to IFTTT webhooks. These webhooks triggered alerts via email enabling real-time remote notification. The MQTT connection flow of the eight sensors is shown in Figure 2, with data from four sensors monitored, analysed and presented in this paper.



**Fig. 2:** The ESP32-based IoT system communication with cloud platform.

The measurement accuracy of the sensors was also considered in the methodology. The DHT22 sensors were capable of measuring ambient temperature in the range  $-40\text{ }^{\circ}\text{C}$  to  $80\text{ }^{\circ}\text{C}$  with an accuracy of  $\pm 0.5\text{ }^{\circ}\text{C}$  and relative humidity from 0 to 100% with an accuracy of  $\pm 2\%$ . These specifications ensured reliable monitoring of environmental conditions and to account for any potential measurement errors.

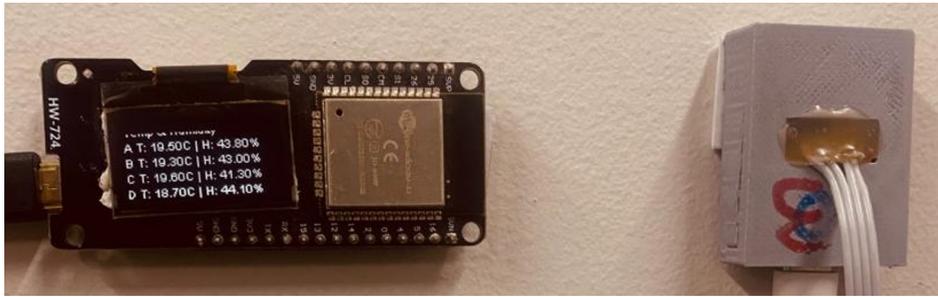
Following the identification of three critical locations requiring environmental monitoring, the system was designed, and the necessary components were procured, to enable implementation. To establish standard environmental conditions, the referenced values for temperature and humidity were defined based on the relevant literature [2, 5, 6, 8, 9]. Table 2 presents the selected ambient temperature and humidity for three locations identified in this work, aligning with recommended ISO-ASTM 52928 ranges specified in Table 2. It is important to note that while specific humidity ranges during the sieving process were not found in the literature, humidity at this location was continuously monitored, consistent with the other monitored areas.

**Table 2.** The system operating conditions.

Name	Conditions		Alarm system
	Temperature	Humidity	
Ambient condition	Temperature 15 – 25 °C	Humidity 20 - 55 %	Alarm on when goes above / below the set threshold
Stored powder	Temperature 15 – 25 °C	Humidity 20 - 55 %	Alarm on when goes above / below the set threshold
Sieving module	Temperature 15 – 25 °C	Humidity 20 - 55 %	Alarm on when goes above / below the set threshold

## 2.2 Monitoring of ambient conditions near the operational areas

For monitoring of ambient conditions in the room, DHT22 sensors were mounted on the wall at height of approximately 1.2 meters from the floor as shown in Fig. 3. The OLED was installed next to one of the sensors to display immediate feedback in real-time. This setup allowed users to quickly monitor environmental conditions on-site without relying solely on the web interface.



**Fig. 3.** An OLED display and a DHT22 sensor mounted on the wall to monitor ambient conditions.

Two locations were selected for ambient monitoring: one sensor was placed near the sieving module station to monitor the condition during the sieving process, and the other sensor was positioned close to the powder bin where un-sieved powder was kept (see Fig. 4). These locations were determined to provide representative environmental readings for each specific operational area.



**Fig. 4.** Sensors monitoring ambient conditions (a) near the stored powder and (b) near the sieving module.

### 2.3 Monitoring of ambient conditions during the powder storage

To monitor powder temporarily stored in bins, a sensor was installed inside the storage bin. The original plastic lid was modified by cutting out a hollow section, which was replaced by a custom-designed lid that housed the sensor and was securely welded to prevent any leakage. Fig. 5 shows the custom-designed bin used for the temporary storage of used powder.



**Fig. 5.** A custom-designed lid housing a DHT22 sensor for monitoring conditions inside the storage bin.

### 2.4 Monitoring of ambient conditions during the sieving process

To enable the monitoring during the sieving process, a round stopper was purchased and modified to house the sensor. A hole was drilled into the stopper to securely insert the sensor against its inner surface as shown in Fig. 6.

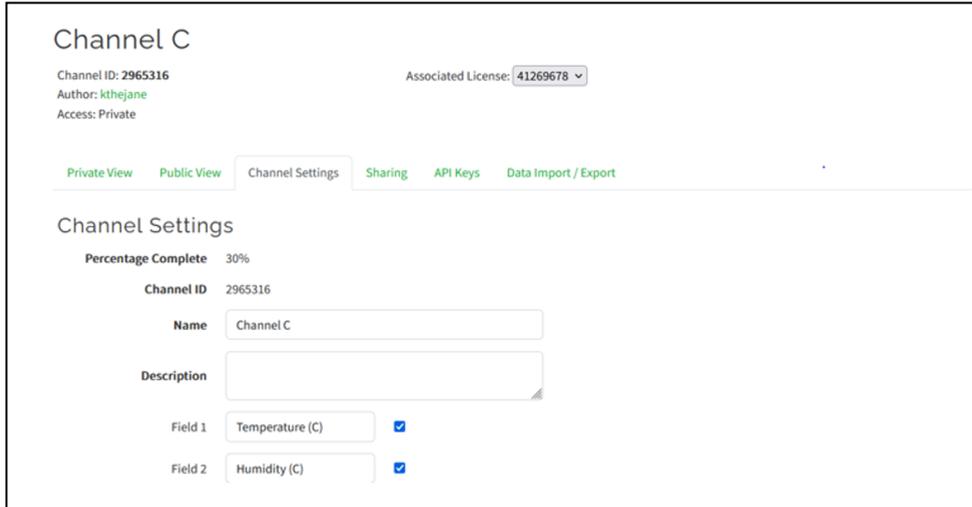


**Fig. 6.** Custom round stopper enclosure integrating a DHT22 sensor for monitoring ambient conditions inside the sieving module.

The sensor inside the sieving module was accommodated by including a lever ball valve that controlled the flow of gases by either fully opening or shutting off the flow as shown in Fig. 6. The sensor power cable was routed through the hole without interfering with any mechanical operation of the sieving equipment. Sealing tape was wrapped around the threads of the stopper to prevent any air ingress into the system. This ensured that the sensor readings reflected only the internal conditions of the sieving equipment. During the sieving process, the bin is opened every 30 minutes for approximately 5 seconds to allow the powder to flow inside the dosing aperture which leads to the sieving unit. This brief duration of 5 seconds is used to prevent the overfilling or jamming of the dosing unit.

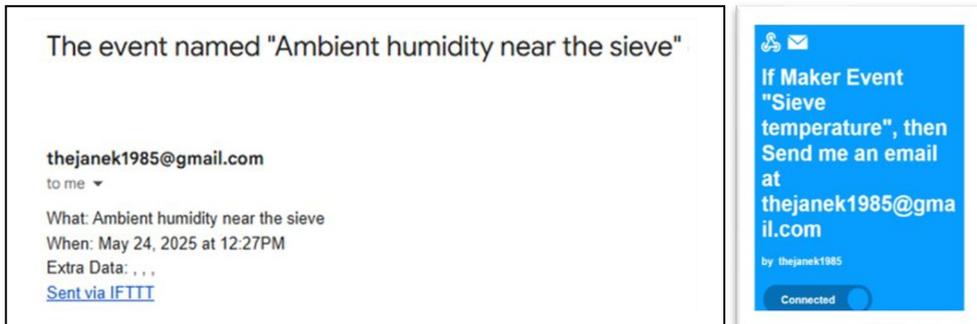
## 2.5 Data collection and display

Sensor data was collected from a unique channel ID and Read API key provided by the ThingSpeak cloud platform as illustrated in Fig. 7. The user account was created by enabling a new server profile secured with the author's name, ID, and password to protect access to the data stored. To ensure data acquisition from each location, four channels were created. The source code obtained from ESP32 was integrated for real-time communication between the ESP32 microcontroller and the ThingSpeak cloud platform.



**Fig. 7.** Channel ID and Read API Key configuration for ThingSpeak monitoring and visualisation.

To enhance the system response, the trigger alert from the IFTTT application was integrated into the system to allow notification if the sensor data rose above the threshold using the custom applets. In this setup, the temperature and humidity data stream from an IoT device to the ThingSpeak platform was monitored by sending an email as shown in Fig. 8 if data exceeded a threshold value.

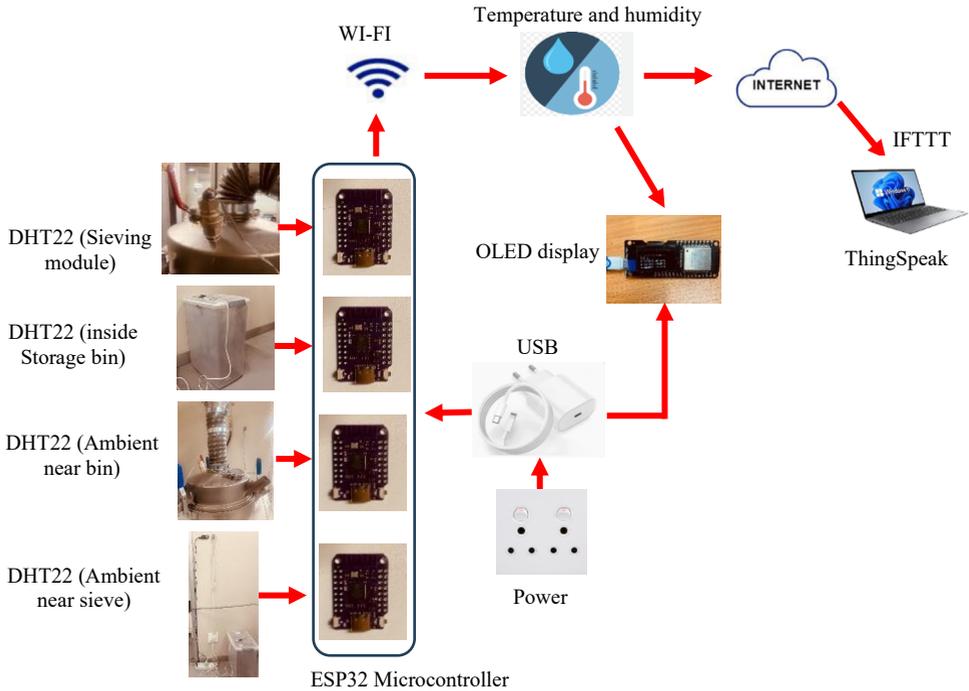


**Fig. 8.** IFTTT Email alert setup for the monitoring system.

## 2.6 Temperature and humidity monitoring system workflow

The workflow of the system is shown in Fig. 9. The system comprised DHT22 digital sensors for environmental sensing, ESP32 microcontrollers for data processing and wireless communication, and OLED displays for real-time onsite feedback. Each ESP32 module was powered via a USB cable and connected to a Wi-Fi network and the MQTT protocol was used for cloud communication. The data collected by the sensors was transferred locally on the ESP32 microcontroller and to ThingSpeak via the internet. In situations where the system failed to perform as intended, such as data transmission errors or sensor instability, a systematic troubleshooting process was followed. This included checking sensor calibration, verifying code logic, confirming Wi-Fi connectivity and replacing faulty components if necessary.

Data received from the sensors were displayed locally on an OLED screen and simultaneously transmitted to ThingSpeak for remote monitoring and logging.



**Fig. 9.** Illustration of the system operational flow.

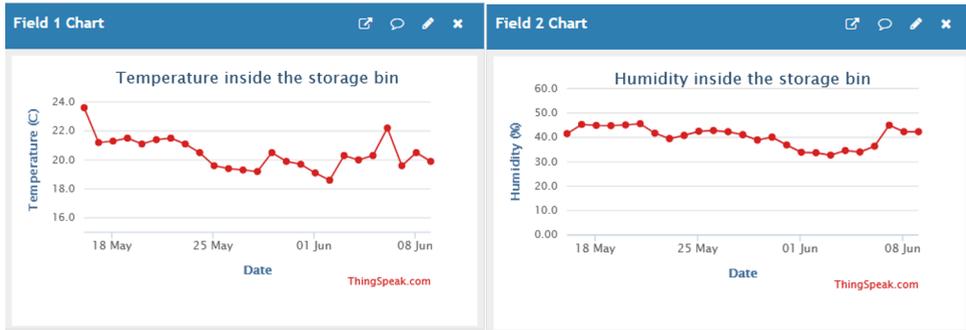
Measurements were recorded at an interval of 1 to 2 seconds for the different sensors. Data was visualised and analysed on a dashboard using graphical representation. If the temperature or humidity was greater than the condition provided, an email was sent to the device using the IFTTT application. Real-time access to this data allowed operators to take immediate corrective action if environmental conditions exceeded the recommended range.

### 3 Results and discussion

In this section all the results collected from different locations are presented, illustrating different graphs in areas that were monitored in this study. Each subsection includes the temperature and humidity graphs, and the results from ThingSpeak visualisation and MATLAB ThingSpeak data explorer platforms. The ThingSpeak visualisation indicates the real-time data captured daily, while the MATLAB analysis compares data from two specific dates spaced three weeks apart, with each dataset representing a 24-hour period.

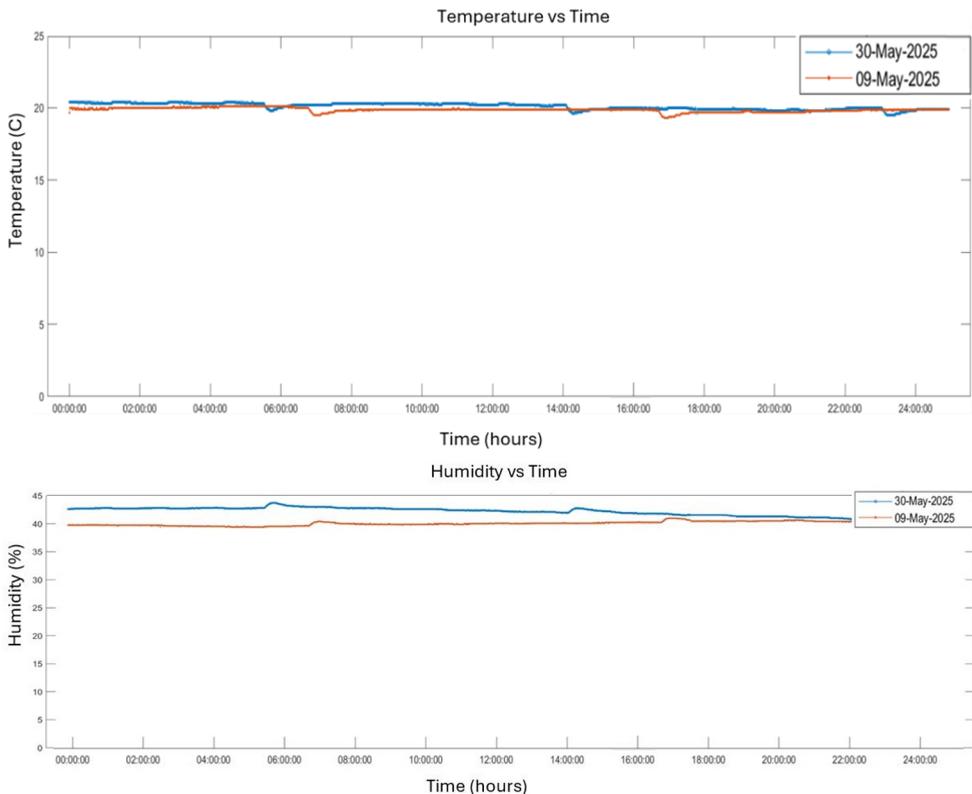
#### 3.1 Visualisation of data collected from the storage bin

The results in Fig. 10 display the continuous monitoring inside the storage bin. The temperature monitoring system seamlessly updates and displays real-time data on the ThingSpeak field charts. The comprehensive information includes dates the data was captured, current temperature and humidity readings and a graphical representation of temperature and humidity trends.



**Fig. 10.** Real-time monitoring of ambient condition inside the storage bin over 25 days.

The powder remained in the storage bin for over three weeks. Fig. 11 displays the trend in temperature and humidity recorded on the two selected dates. The results show the small variation in both parameters indicating stable conditions. Throughout the recorded periods, both temperature and humidity remained within the required specifications.

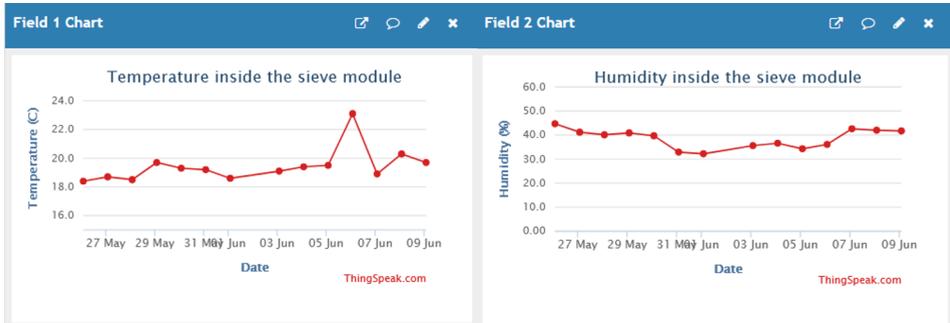


**Fig. 11.** ThingSpeak data showing ambient condition trends inside the bin over three weeks of monitoring.

### 3.2 Visualisation of data collected from the inside of the sieve module

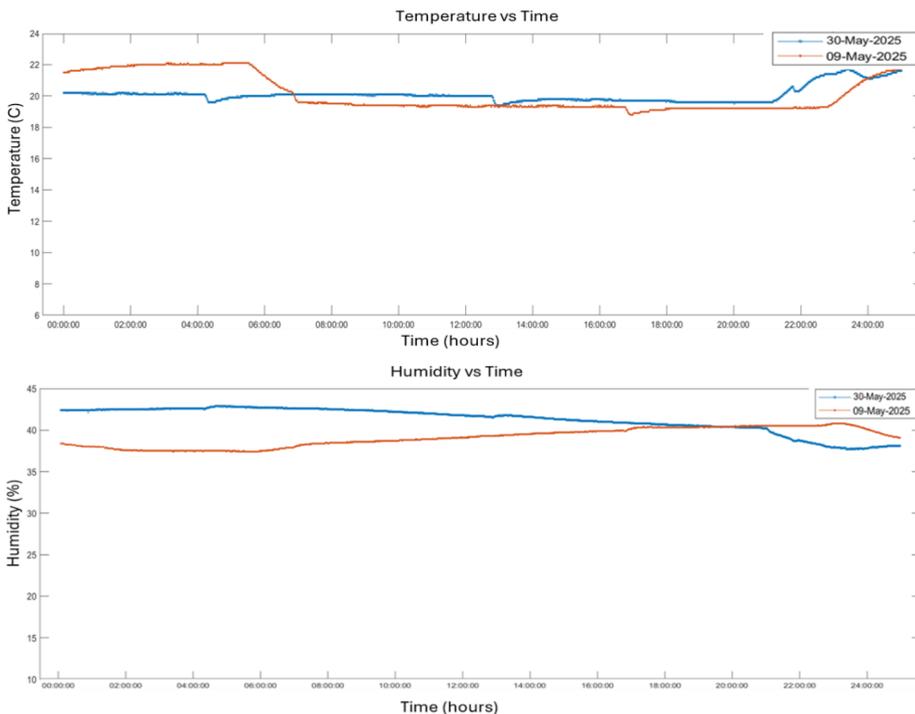
Fig. 12 shows the continuous monitoring conditions inside the sieving module. The data presentation on the ThingSpeak platform ensured a dynamic and up-to-date visualisation of

environmental conditions. The graphical results for both temperature and humidity showed the fluctuations of the readings which remained within the specified limits.



**Fig. 12.** Real-time monitoring of ambient condition inside the sieving module over 14 days.

Data was also gathered during the sieving process and compared with historical data from three weeks back. As illustrated in Fig. 13, data was successfully recorded using MATLAB ThingSpeak data explorer to monitor any change in ambient conditions. The monitoring results present continuous data collection over three weeks. Despite observed fluctuations, the ambient condition remained within the required specifications.



**Fig. 13.** MATLAB visualisation of ambient condition during the sieving process.

### 3.3 Visualisation of data collected from near the sieving module

Fig. 14 presents the continuous monitoring of ambient conditions near the sieving module. Real-time measurements were consistently collected and recorded and logged on the ThingSpeak platform.

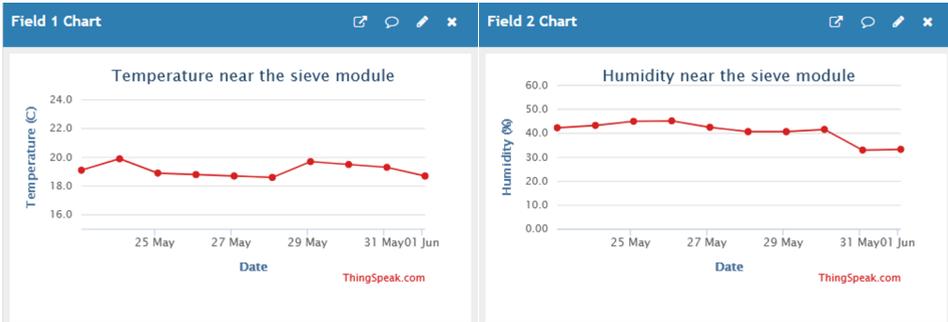


Fig. 14. Real-time monitoring of ambient condition near the sieving module over 10 days.

Data was visualised using the MATLAB ThingSpeak Data Explorer to analyse environmental measurements near the sieving module. As illustrated in Fig. 15, minor variations in the data were observed indicating temporary changes in ambient conditions. Nevertheless, the environment near the sieve was effectively monitored and remained within the specified conditions.

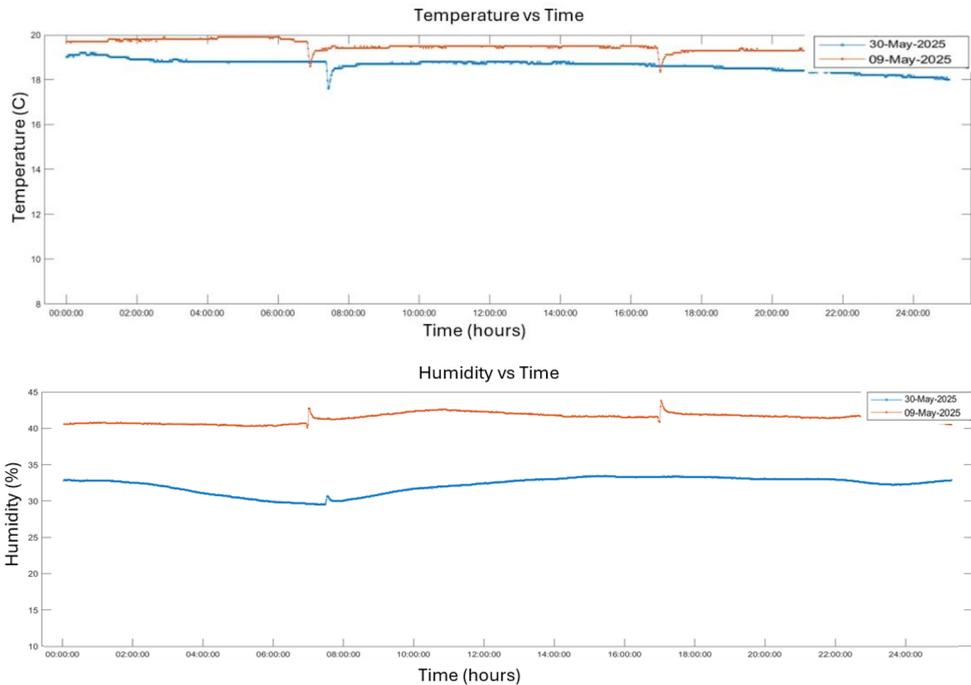


Fig. 15. MATLAB visualisation of ambient condition near the sieving module.

### 3.4 Visualisation of data collected from near the storage bin

Fig.16 and Fig. 17 illustrate the continuous monitoring of ambient conditions near the storage bin. These conditions were also consistently recorded in real-time using the ThingSpeak platform. On the 16<sup>th</sup> of May, a slight temperature increase was observed reaching 24.5 °C, however, as shown in Field 1, the temperature remained within the specifications.

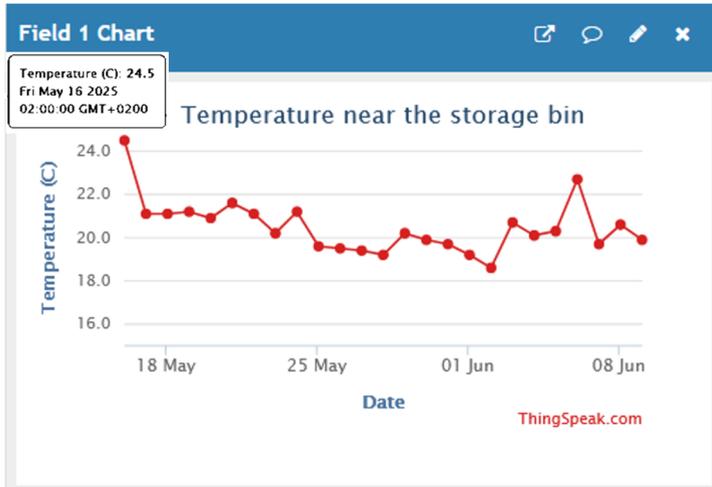


Fig. 16. ThingSpeak temperature condition results near the storage bin over 25 days.

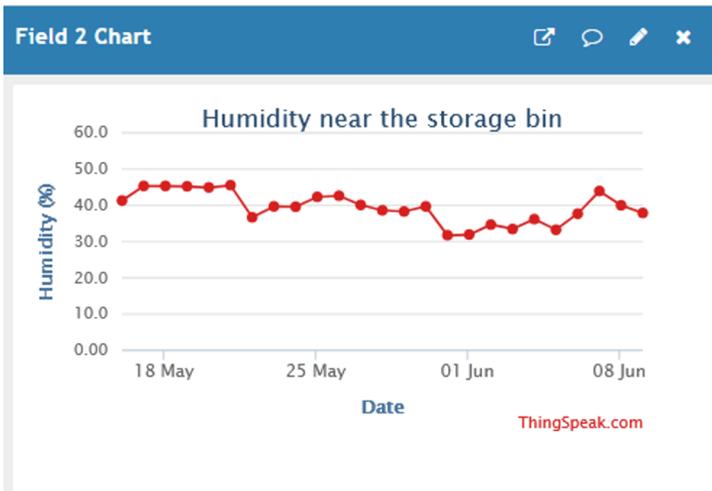
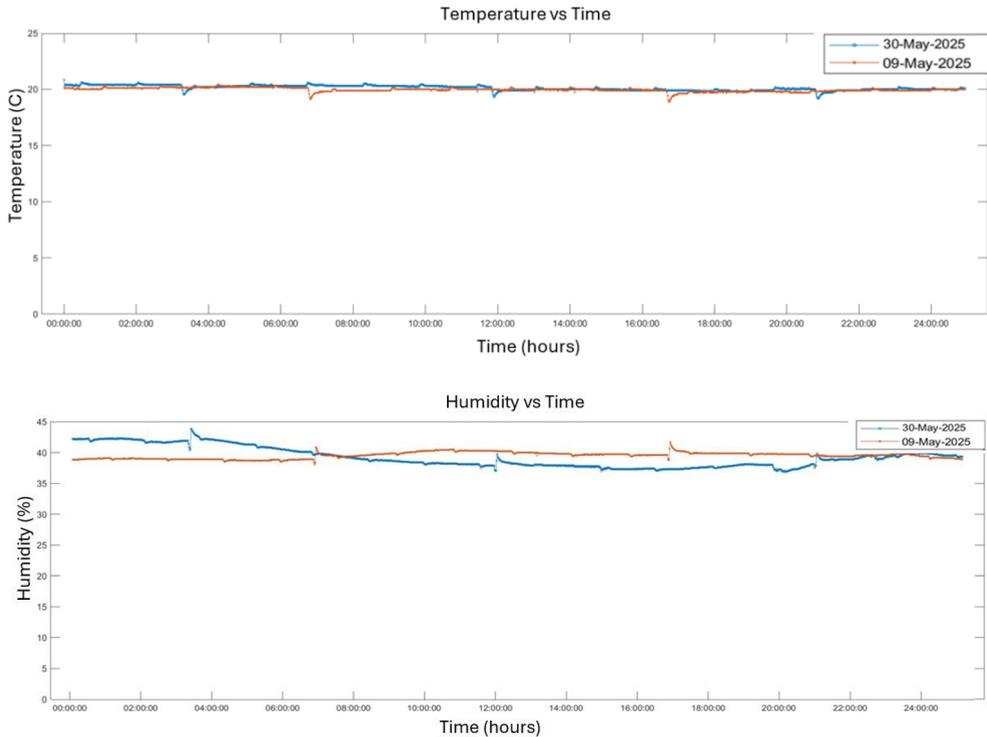


Fig. 17. ThingSpeak humidity condition results near the storage bin over 25 days.

Data was visualised using the MATLAB ThingSpeak Data Explorer to analyse environmental measurements near the stored powder. This extended monitoring was aimed at identifying any significant environmental changes, however, only minor variations were observed as shown in Fig. 18. These fluctuations corresponded with those recorded near the sieving module, suggesting that the ambient condition in the room was almost the same. Nevertheless, the environment around the stored powder was effectively monitored and remained within the specified limits.



**Fig. 18.** MATLAB visualisation of ambient condition near the storage bin.

## 4 Conclusion

This study presented the design and implementation of the temperature and humidity system for continuous monitoring during the powder handling and storage processes. The integration of Internet of Things (IoT) technologies, specifically using platforms such as ThingSpeak and MATLAB, played a crucial role in real-time data acquisition and analysis. The continuous monitoring system ensured the reliability and repeatability of the processes over time. Minor fluctuations were detected across all monitored areas, likely resulting from short term disturbances such as door opening that caused a temporary change in ambient conditions.

For the temperature parameter, the acceptable ranges were set between 15 °C and 25 °C. The recorded measurements obtained from the monitored areas remained within this range, with values consistently above 18 °C and below 24.5 °C. In terms of humidity, the threshold was not to exceed 55% and the recorded values remained below 50%. The armed response system was also effective to register an alert for any change that went beyond the threshold, however, no such events occurred during the monitoring period.

Overall, the results confirmed the effectiveness of the monitoring system to reliably record sensor data from different areas and ensuring that ambient conditions are controlled during the powder handling and storage processes.

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