IoT Enabled Real Time Monitoring and Management of Tobacco Curing Barns

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Citation | Jan. T, Hidayat. H, Usman. M, Khan. S. S, "IoT Enabled Real Time Monitoring and Management of Tobacco Curing Barns", IJIST, Vol. 8 Issue. 3 pp 1281-1298, June 2026
DOI: https://doi.org/10.33411/IJIST/1924
Received April 25, 2026 **Revised|** May 28, 2026 **Accepted|** June 04, 2026 **Published|** June 16, 2026.

Tobacco is one of the major cash crops in Pakistan, and its quality and market value greatly depend on its curing process. Proper curing requires continuous maintenance of temperature and humidity during the yellowing, leaf drying, and stem drying stages. Traditional curing methods commonly used in Pakistan rely on manual supervision and human judgment, often resulting in inconsistent curing quality, high labor costs, excessive energy consumption, and inefficient environmental management. These limitations create the need for an intelligent and automated tobacco curing solution. This research proposes an Internet of Things (IoT)-based real-time monitoring and management system for tobacco curing barns. The system uses a DHT11 sensor to continuously collect temperature and humidity data from the curing barn. An ESP32 microcontroller processes the sensor readings and automatically controls fans and a mist maker to maintain optimal curing conditions. A Firebase Realtime Database is integrated for cloud-based data storage and synchronization, while a Flutter-based mobile application enables real-time monitoring and control operations. The developed prototype demonstrated successful monitoring and automated control of temperature and humidity under controlled testing conditions, enabling real-time environmental management during the tobacco curing process. The system exhibited an average response time of approximately 2 seconds during stage transitions and successfully supported automated stage-wise operation for the yellowing, leaf drying, and stem drying phases. The prototype evaluation focused on validating system functionality, sensor-actuator integration, and cloud-based monitoring capabilities. The proposed automated approach provides a framework for improving operational efficiency, enhancing environmental control consistency, and reducing dependence on continuous manual supervision during the curing process. Overall, the proposed IoT-based tobacco curing system presents a low-cost and scalable solution for real-time monitoring and automated environmental management in tobacco barns, with potential benefits for curing consistency and operational efficiency in Pakistan.

Keywords: Tobacco Curing; Internet of Things (IoT); ESP32 microcontroller; Real-Time System; Flutter Mobile Application; Sensor-Based Automation

Introduction:

Tobacco stands as one of the primary cash crops in Pakistan, its market value and quality critically dependent on the curing process. Curing involves the constant environmental maintenance of temperature and humidity during a series of stages: yellowing, leaf drying, and stem drying [1]. Such processes are usually done at a manual level, increasing costs but achieving unreliable uniformity and quality due to inefficient control systems [2].

With the new innovations in technology, especially the Internet of Things (IoT), agriculture processes can now be monitored and controlled remotely which greatly improves precision, effectiveness, and consistency [3]. This project describes the development of an IoT-based real-time monitoring and automatic control system for temperature and humidity regulation in tobacco curing barns. The system utilizes sensors interfaced with an Arduino microcontroller that regulates environmental fans and a mist maker based on the readings [4].

The project additionally integrates a mobile application developed with Flutter that connects to the system through Firebase. Users can access real-time information, notifications, and remotely manage the curing process both manually and automatically through the app. This smart technology streamlines the curing process which enhances the quality of the final product. It is an easy and low-cost technology solution for small and medium-scale tobacco growers in Pakistan [5].

The important post- harvest step that has a big impact on the flavor, chemical makeup, and general quality of tobacco leaves is the curing process. This procedure has historically mainly relied on manual supervision, which is subject to errors because of human error and changes in the environment. Recent studies have concentrated on incorporating Internet of Things (IoT) technologies for accurate real-time monitoring and control of critical parameters like temperature and humidity inside curing barns [6] in order to address these issues. In order to improve process management and increase the accuracy of environmental data collection, a multi-probe thermo-hygrometer that enables simultaneous measurement of multiple locations within the curing barn was developed. The rapid advancement of the Internet of Things (IoT) has transformed modern agriculture by enabling intelligent monitoring and automated control systems for many farming applications [7]. IoT technologies have been widely adopted in controlled agricultural environments such as greenhouses, where real-time monitoring of environmental parameters and automated decision-making help improve productivity, efficiency, and crop quality [8][9]. Similar requirements exist in tobacco curing barns, where maintaining appropriate temperature and humidity conditions is essential for achieving high-quality cured tobacco leaves. By integrating sensors, communication technologies, and automated control mechanisms, IoT-based systems provide an effective solution for reducing manual labor and improving process reliability [10].

In tobacco curing, accurate identification and prediction of curing stages are important for ensuring proper drying and maintaining the leaf quality. Traditional manual monitoring methods are time-consuming and cause human error. Recent technological advancements have introduced sensor-based monitoring, machine learning, deep learning, and image-processing techniques to automatically recognize curing stages and predict curing conditions in real time [11][12]. These intelligent approaches enable proactive environmental adjustments, improve process control, and reduce dependency on manual inspections. Multi-sensor data fusion and image-based assessment methods further enhance the accuracy of curing-stage recognition and provide non-invasive techniques for monitoring leaf conditions during the curing process [13][14].

The integration of IoT, intelligent monitoring, automated environmental control, and data-driven decision-making presents a modern approach to improve the tobacco curing operations [15]. By combining real-time sensor monitoring with automated control strategies, tobacco curing can achieve enhanced consistency, improved leaf quality, greater operational efficiency, and reduced labor requirements [16]. Based on these advancements, this project proposes an IoT-based real-time monitoring and management system for tobacco curing barns. The system incorporates temperature and humidity sensors, stage-based process management, automated fan and mist maker control, cloud-based monitoring, and mobile application integration to optimize the tobacco curing process and improve overall curing performance.

A crucial post-harvest procedure that greatly affects the flavor, color, texture, and general quality of tobacco leaves is curing. This procedure has historically been handled by hand, mainly depending on farmers' expertise and simple instruments like hygrometers and thermometers. Although helpful, these techniques can't guarantee constant environmental conditions, which can result in mistakes, inefficiencies, and a decline in product quality.

Farmers currently keep an eye on the humidity and temperature inside curing barns using stand-alone devices [17]. These devices need continual supervision and only offer simple readings. To maintain ideal conditions, farmers must manually check the curing barns every hour of the day, which is a time-consuming and labor-intensive procedure. Farmers are vulnerable to delays in reacting to temperature and humidity changes because they are unable to remotely monitor and manage the environment [18]. Over-curing, under-curing, or the growth of mold can result from even small departures from the optimal range. Continuous manual adjustments also raise the possibility of human error, which jeopardizes the yield and curing process even more. Farmers' time and resources are strained by this reliance on antiquated techniques, which also makes it more difficult for them to efficiently handle other crucial agricultural duties.

The current system's shortcomings lead to a number of detrimental effects

The quality of cured tobacco leaves varies.

Energy waste as a result of ineffective manual control

Increased time and labor expenses

Revenue loss as a result of lower market value and lower-quality products

In the end, the lack of intelligent automation lowers output and disadvantages small-scale farmers in markets where quality is a determining factor. The entire curing procedure is still antiquated and unscalable. An IoT-based no-touch solution would give an oversight increase in the accuracy of labor to environment ratio, the control over the curing environment, operational efficiency, and most importantly, the quality of the end product. The main contributions of this article are highlighted as follows:

Studied the existing tobacco curing process, including the manual supervision, environmental conditions, resource utilization, while identifying key challenges in the traditional system.

Developed an IoT-based real-time monitoring system that continuously monitored temperature and humidity and have enabled remote access through a mobile application [19].

Automated the curing environment using fans and misting systems to optimize curing conditions [20], improve efficiency and reduce unnecessary resource consumption.

Implemented alert and data visualization features to support quick decision making and process optimization through data analysis [10].

Novelty of the study:

Several studies have investigated IoT-based monitoring systems for tobacco curing and agricultural applications; however, many existing solutions primarily focus on environmental monitoring and data collection. The proposed system extends beyond monitoring by integrating real-time sensing, automated environmental control, cloud-based data management, and mobile application support within a unified platform.

The novelty of this study lies in:

The integration of ESP32-based sensing and automated actuator control for maintaining temperature and humidity conditions during different tobacco curing stages.

The implementation of stage-based curing management covering yellowing, leaf drying, and stem drying phases within a single automated framework.

The use of Firebase Realtime Database for cloud-based monitoring, synchronization, and historical data storage.

The development of a Flutter-based mobile application that enables real-time monitoring and remote management of the curing process.

The incorporation of barcode-based batch tracking to support traceability and retrieval of historical curing records.

The design of a low-cost and scalable architecture suitable for deployment in small and medium-scale tobacco curing operations in developing regions.

Research Objectives:

The primary objective of this study is to design, develop, and evaluate an Internet of Things (IoT)-based real-time monitoring and management system for tobacco curing barns that supports automated environmental control and remote supervision of the curing process.

The specific objectives of the study are:

To investigate the limitations of conventional manual tobacco curing practices and identify key environmental parameters affecting curing quality.

To design and implement an IoT-based architecture integrating temperature and humidity sensing, cloud connectivity, and automated actuator control for tobacco curing barns.

To develop a real-time monitoring framework using ESP32, Firebase Realtime Database, and a Flutter-based mobile application for remote access and management.

To implement stage-based automation for the yellowing, leaf drying, and stem drying phases of the tobacco curing process.

To evaluate the functional performance of the developed prototype in terms of real-time monitoring, cloud synchronization, actuator response, and automated stage management.

To demonstrate the feasibility of applying low-cost IoT technologies for improving operational efficiency and reducing dependence on manual supervision in tobacco curing operations.

Literature Review:

Tobacco Curing is a critical post-harvest process which directly affects the physical appearance, aroma, texture and overall quality of the tobacco leaves [1]. For this an intelligent IoT-based temperature and humidity monitoring system was developed for tobacco curing barns to continuously monitor environmental conditions and improve curing efficiency through real-time data transmission and analysis [2]. Another IoT-based monitoring system using a multi-probe thermo-hygrometer was proposed to observe tobacco curing conditions accurately and reduce the need for manual supervision during the curing process [6].

The role of IoT in modern agriculture has been widely studied to support environmental monitoring and automation [19]. Research on greenhouse agriculture also highlighted various IoT technologies, communication protocols, and applications that enable smart agricultural management and precision farming practices [3]. Similarly, intelligent agricultural network systems were introduced to improve agricultural productivity and resource management through sensors and automated communication technologies [7].

Prediction and intelligent decision-making in tobacco curing have also gained significant attention [11]. A state prediction method based on model fusion techniques was proposed to improve the accuracy of tobacco curing stage prediction and environmental adjustment. Deep learning techniques were also used for recognizing tobacco leaf curing stages, demonstrating the effectiveness of artificial intelligence in automating tobacco processing operations [12]. Multi-sensor data fusion methods were introduced to recognize tobacco curing states and predict temperature rise time more accurately by combining data from multiple environmental sensors [13]. Image processing techniques were also applied to recognize typical tobacco curing stages and monitor leaf conditions throughout the curing process [21]. In addition, deep learning algorithms were used to identify the yellowing degree of tobacco leaves during curing, providing an automated approach for tobacco quality evaluation [12].

Advanced IoT architectures have further improved monitoring and processing capabilities in tobacco curing systems [10]. An edge-enabled IoT framework was proposed for real-time tobacco quality monitoring, integrating edge computing technologies to reduce processing delays and improve decision-making performance. Research on the stem-drying stage of flue-cured tobacco showed that proper dry-bulb temperature control significantly affects the final quality of tobacco leaves [1]. Several studies focused on IoT-based agricultural monitoring systems that can support tobacco curing applications [18]. An IoT-enabled smart monitoring system was developed for agricultural environments to continuously collect environmental data and support efficient crop management [8]. Another smart tobacco curing and monitoring system integrated edge computing technologies to provide intelligent monitoring, low-latency processing, and automated control functions. Real-time agriculture monitoring systems were also developed to support sensor integration and wireless communication for smart farming applications [22]. IoT-based smart agriculture monitoring systems were designed to monitor environmental conditions and support automated agricultural operations efficiently [17].

Precision agriculture solutions have additionally contributed to improved agricultural resource management [9]. An IoT-based system for water harvesting, moisture monitoring, and crop monitoring was proposed to support precision agriculture practices and efficient environmental management [23]. IoT-enabled precision agriculture ecosystems were also introduced to optimize crop management through intelligent sensing and automated decision-making technologies [24]. Cloud computing integration has enhanced the scalability and accessibility of agricultural IoT systems. Cloud-based IoT solutions were proposed to improve agricultural sustainability and operational efficiency through remote monitoring and cloud data management [5]. A real-time cloud-enabled IoT crop management platform was also developed to support continuous monitoring and remote access to agricultural information [25]. Another IoT-based agriculture monitoring system introduced a double-tier data storage facility to improve data reliability and accessibility in smart farming environments [26].

Safety and hazard management in tobacco curing have also been studied [27]. An IoT-based early fire detection system for tobacco ovens was developed to detect fire hazards in real time and improve operational safety during the curing process. Artificial intelligence techniques have further enhanced agricultural monitoring systems. A machine learning-based intelligent monitoring system was introduced for smart farming applications, demonstrating improved monitoring accuracy, predictive analysis, and automated decision-making capabilities.

Table1. Literature Comparison Table

Study	Monitoring	Automated Control	Cloud Integration	Mobile Application	Stage-Based Curing Management	Batch Tracking
[2]	✓	✗	✗	✗	✗	✗
[6]	✓	✗	✗	✗	✗	✗
[8]	✓	✓	Partial	✗	✗	✗
[11]	✓	Prediction-Based	✗	✗	✓	✗
[13]	✓	Prediction-Based	✗	✗	✓	✗
[10]	✓	Partial	✓	✗	✗	✗
Proposed System	**✓**	**✓**	**✓ (Firebase)**	**✓ (Flutter App)**	**✓**	**✓ (Barcode-Based)**

Table 1 shows that most existing studies focus on either environmental monitoring, intelligent prediction, or partial automation. However, they do not provide a complete solution that combines real-time monitoring, automated environmental control, cloud-based data management, mobile application support, stage-wise curing management, and batch traceability within a single platform. The proposed system integrates all these features, providing a more comprehensive and practical solution for tobacco curing barns.

Research Gap:

There are several studies on IoT-based monitoring systems, intelligent prediction models and smart agriculture solutions for tobacco curing, but there are still big gaps in the literature. Most of the existing systems are mainly concerned with environmental monitoring and data collection, but not with fully automated environmental control. Similar to the prediction-based approaches, curing stage recognition and forecasting are also focused, though the real-time actuator integration and practical deployment support are often lacking. In addition, very few studies have focused on the issues of cloud-based data management, mobile application integration, and traceability mechanisms for keeping historical curing records. Hence, there is a need for a unified low-cost IoT solution for real-time monitoring, automated stage-wise environmental control, cloud connectivity, mobile access, and batch tracking. The proposed system addresses these gaps by integrating ESP32-based sensing, automated fan and mist-maker control, Firebase Realtime Database, a Flutter mobile application, and barcode-based batch tracking within a single platform suitable for tobacco curing operations.

Challenges & Limitations in Current Systems:

The challenges and limitations in the current system are discussed below:

Existing tobacco curing systems mainly focus on monitoring temperature and humidity only, while lacking complete automation and intelligent environmental control capabilities [2].

Real-time monitoring systems still require partial manual supervision during the curing process, reducing operational efficiency and consistency [6].

Many IoT-based agricultural systems face challenges related to communication reliability, interoperability, and high implementation costs in large-scale deployments [3].

Intelligent agricultural network systems often experience limitations in network stability, scalability, and integration between heterogeneous devices and sensors [7].

Prediction-based tobacco curing models may suffer from reduced accuracy when environmental conditions change dynamically or when insufficient training data is available [11].

Multi-sensor data fusion methods increase system complexity and may lead to higher processing overhead and maintenance requirements [13].

Maintaining precise dry-bulb temperature during the stem-drying stage remains difficult due to environmental fluctuations and inconsistent heat distribution [1].

IoT-enabled agricultural monitoring systems often lack intelligent automated response mechanisms and mainly focus on environmental data collection [8].

Real-time agriculture monitoring systems face issues related to wireless communication range, sensor reliability, and power consumption [22].

Methodology:

The suggested Internet of Things (IoT)-based temperature and humidity control system for Pakistani tobacco curing barns is thoroughly analyzed and designed. The objective is to reduce manual labor while increasing quality, consistency, and energy efficiency by automating the curing process [2]. Intelligent decision-making and accurate environmental regulation within the barns are made possible by this system, which combines sensor-based monitoring, real-time cloud integration, and mobile control [5].

A crucial post-harvest procedure, tobacco curing has historically relied on manual inspection and adjustments, which frequently leads to quality variation, increased labor, and resource inefficiency [1]. This system turns traditional techniques into smart agriculture by incorporating IoT technologies, which guarantee remote supervision, automated control, and data-driven adjustments [19].

Functional Requirements:

The system's purpose is to keep an eye on and control the environmental factors in a tobacco curing barn. Using the proper sensors, it continuously measures temperature and humidity and sends the data in real time to a Firebase cloud database [4]. In order to maintain ideal curing conditions, the system uses this data to automatically control actuators, such as two fans and a mist maker [20]. In particular, Fan 1 starts when the temperature rises above the specified upper limit, Fan 2 starts when the temperature falls below the lower threshold, and the mist maker starts when the humidity falls below the necessary threshold. Additionally, users can communicate with the system remotely through a mobile application built with Flutter. This app allows users to view current temperature, humidity, stage of curing, and remaining time for that stage in real time.

Non-Functional Requirements:

The system must meet a number of Non-functional Requirements in order to function in real-world settings. In order to integrate more curing barns in the future without requiring major architectural changes, the system needs to be scalable [22]. It should be extremely dependable, guaranteeing precise data gathering and steady actuator operation with few mistakes or malfunctions. Another important factor is usability; in order to serve users with little technical expertise, the mobile application needs to have an easy-to-use interface. In order to prevent disruptions in the curing process, the system should also have high availability [28], meaning it should run around the clock with little downtime. Lastly, security is crucial; in order to safeguard sensitive operational data and avoid unwanted control, only authorized users should be allowed access to the system.

System Architecture:

The suggested IoT-based tobacco curing system's architecture is made to guarantee smooth interaction between cloud services, hardware parts, and an intuitive mobile application. A microcontroller, like the Arduino ESP32, serves as the central processing unit and is at the heart of the system. Temperature and humidity sensors, such as the DHT11, are connected to this microcontroller and are used to continuously monitor the conditions inside the tobacco curing barn. The microcontroller processes the gathered data before sending it to a cloud platform via a Wi-Fi module, like the ESP8266, to allow for remote access and real-time data logging [25]. The system has actuators, namely two fans and a mist maker [29], to maintain ideal curing conditions. Fan 1 lowers high temperatures, Fan 2 raises the temperature when it drops below the desired threshold, and the mist maker raises humidity when it drops too low. Based on preset thresholds that are programmed into the microcontroller, these actuators are automatically controlled. Sensor data is transferred to Firebase, a real-time cloud database that manages system status, stage information, and notification services in addition to storing environmental data. The user interface is a mobile application that was created with the Flutter framework. Along with monitoring real-time data like temperature, humidity, curing stage, and remaining time, this app lets users start, stop, and reset the curing process. The system facilitates seamless communication between all parts, allowing for automation, remote curing process supervision, and real-time decision-making. In the process of curing tobacco, this architecture minimizes human error and manual labor while guaranteeing efficiency, dependability, and user convenience [30].

The mobile application, cloud backend (Firebase), and hardware control make up the three primary parts of the system. Temperature and humidity readings from the sensors are sent to Firebase continuously. To show this data to the user, the Flutter application retrieves it in real time. Control logic is automatically run to activate the corresponding fans or mist maker based on the stage-specific thresholds.

Phase 1 Yellowing

Phase 2 Drying of the Leaves

Phase 3 Drying of the Stem

The system maintains optimal curing conditions while automatically moving through these phases.

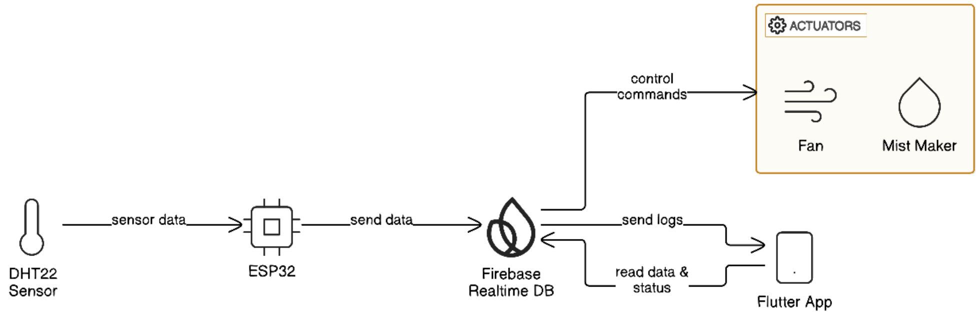

Figure 1. System architecture of the IoT-based tobacco curing system.

System Flowchart:

The proposed IoT-based tobacco curing system operates automatically in accordance with a logical flow to guarantee ideal environmental control during the curing process. The system starts when the user presses the "Start" button to start the curing process via the mobile application. Once started, the microcontroller (such as an ESP32) begins reading real-time data from the DHT11 sensor, which measures the temperature and humidity inside the curing barn.

The microcontroller analyzes the current environmental conditions after receiving the sensor data and compares them to predetermined thresholds depending on the particular curing stage. Fan 1 is turned on to lower the temperature if it rises above the upper limit specified for the current stage. Fan 2 is activated to raise the temperature if it drops below the lower limit. In a similar manner, the mist maker is turned on to restore ideal humidity if it falls below the necessary level. Without human input, these choices are made automatically.

The system continuously updates Firebase with real-time data throughout the process, such as temperature, humidity, remaining time, and current curing stage. The user can then remotely monitor the curing process thanks to the synchronization of this data with the mobile application. When the current stage time expires, the system automatically moves on to the next one after verifying the length of each curing stage. The system stops updating Firebase and suspends all operations if the user hits the "Stop" button. The system returns to the initial state, prepared for a fresh curing cycle, if the user chooses "Reset," clearing the timer and stage data. By ensuring that the curing process is precisely regulated and doing away with the need for manual adjustments, this fully automated flow greatly enhances consistency, efficiency, and quality in the processing of tobacco. Figure 2 shows the system flowchart of the tobacco curing system.

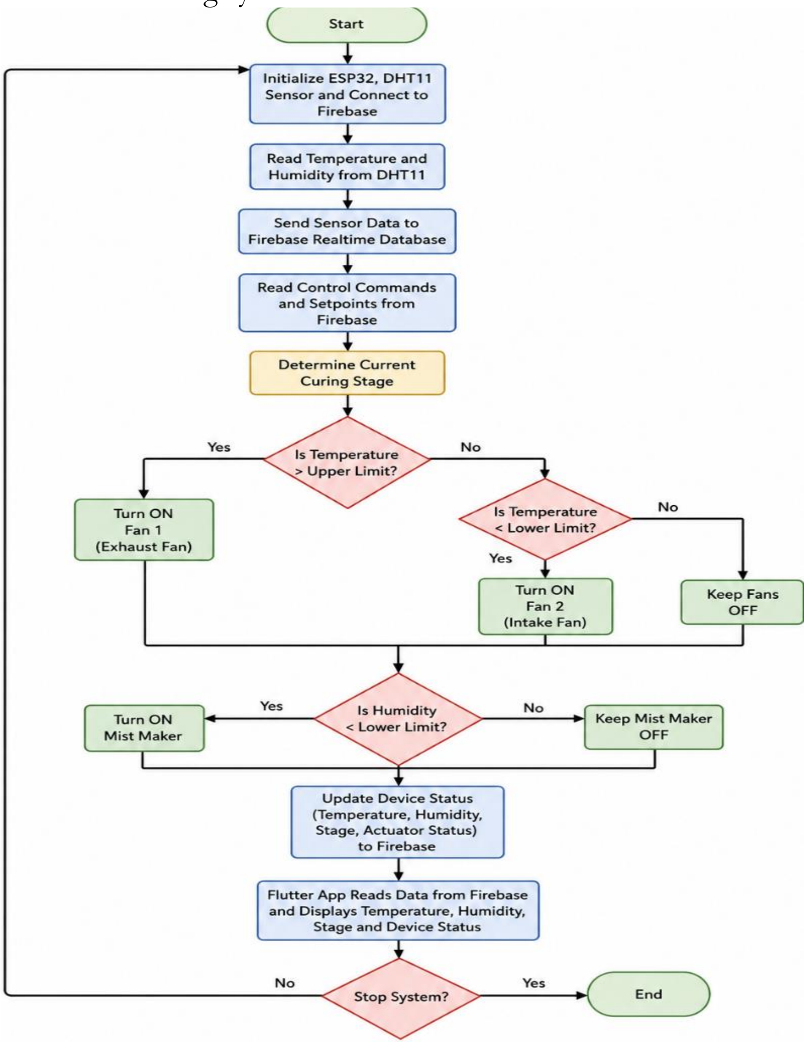

Figure 1. Flowchart diagram of the system

Hardware Design:

In order to monitor the conditions inside the curing barn, the system's hardware design integrates temperature and humidity sensors with a microcontroller (such as an Arduino). Based on sensor readings, the setup uses control elements like fans and a mist maker to adjust humidity and temperature [12]. The system can run in automatic mode thanks to a Wi-Fi module that permits real-time data transmission to Firebase. Reliable wiring and power supply management are also taken into account to guarantee steady performance during continuous operation. In agricultural settings, the overall design strives for affordability, dependability, and simplicity of deployment [15].

Components Used:

Reliability, affordability, low power consumption, and compatibility with Internet of Things applications utilized in remote locations such as tobacco barns served as the guiding principles for the selection of hardware components. For wireless communication and real-time synchronization with the Firebase Realtime Database, the ESP32 microcontroller, a strong and adaptable device with integrated Wi-Fi and Bluetooth capabilities, is the perfect choice. It acts as the system's brain, controlling actuator control, sensor readings, decision-making, and cloud data transmission.

A DHT11 sensor, which continuously measures temperature and humidity with enough accuracy for agricultural applications, is used to monitor the barn's interior environment. The system uses two different kinds of fans to regulate the barn's environment based on these readings. To help release hot air, Fan 1, an exhaust fan, is activated when the temperature rises above the upper threshold for the current curing stage. On the other hand, Fan 2, an intake fan, helps efficiently circulate heat or draw in warmer air when the temperature drops below the lower threshold.

A Mist Maker is included to regulate the humidity. It ensures that the leaves maintain ideal moisture levels throughout the curing process by activating when the humidity falls below the target value for the current stage. For electrical safety and dependable switching, a relay module serves as an interface between the microcontroller and high-voltage AC-powered devices, controlling all of the actuators, including the fans and mist maker.

The microcontroller and actuators are powered by a regulated power supply that can be either 5V or 12V, depending on the specifications of the connected components. Stable system performance and component protection against voltage fluctuations are guaranteed by effective power planning. All things considered, the system can automatically maintain the necessary curing conditions with little assistance from humans thanks to the integration of these hardware components. The table 2 shows the hardware components with their purpose.

Table 2. The hardware components used in the system.

Component	Purpose
ESP32Microcontroller	Central control and communication with Firebase
DHT Sensor	Measures temperature and humidity
Fan1 (Exhaust Fan)	Reduces temperature if exceeds threshold
Fan2 (Blower Fan)	Increases temperature if exceeds threshold
Mist Maker	Increases humidity when it drops below threshold
Relay Module	Control AC- powered devices like fans and mistmaker
Power Supply (5V/12V)	Power microcontroller and actuators

Software Design:

Firebase for smooth communication between the hardware and mobile application, automated environmental control, and effective data handling. The Arduino IDE is used to program the microcontroller logic, which is the central component of the system. The curing process is automatically moved through three predetermined stages by the software using a structured stage-timer algorithm **covering** yellowing, leaf drying, and stem drying. Every stage has a designated duration (which is initially set at one minute for demonstration purposes, but can be changed for real-world applications) and is linked to particular temperature and humidity ranges.

Control Logic:

The environment stays within the intended thresholds thanks to the control logic. Fan 1 (exhaust) is turned on when the temperature rises above the upper limit for a particular stage. Fan 2 (intake) is activated if the temperature falls below the minimum threshold. Similarly, the mist maker is activated to restore ideal moisture when the humidity level drops below the necessary threshold. Based on continuous readings from the DHT11 sensor, these decisions are carried out automatically in real time.

Firebase Integration:

Integration with Firebase, which permits remote monitoring and real-time data logging, is a key component of the software design. The Firebase Arduino library is used to connect the ESP32 to the Firebase Realtime Database. The system periodically adds the most recent temperature, humidity, stage, and system status (e.g., ON, OFF, or Reset) to the database. This enables the mobile application to retrieve and present the user with accurate, current information. All things considered, the software design integrates cloud connectivity, real-time sensing, and automated control to guarantee that the curing process is intelligent and remotely controllable without the need for manual adjustments. Because of this, the system is effective, scalable, and ideal for contemporary agricultural settings.

Mobile Application Design:

For cross-platform Android support, Flutter was used in the development of the mobile application. Users can remotely start, halt, and reset the curing process using the app, which also gives them complete visibility into it.

Experimental Setup:

A laboratory-scale prototype was developed using an ESP32 microcontroller, DHT11 temperature and humidity sensor, relay module, exhaust fan, intake fan, mist maker, Firebase Realtime Database, and a Flutter mobile application. Functional testing was conducted under controlled indoor conditions to verify sensor communication, cloud synchronization, actuator response, stage transitions, and mobile application functionality. The objective of testing was to validate system operation and integration rather than evaluate agricultural field performance.

User Interface:

There are multiple pages in the application

The Welcome Page. It welcomes users with branding and directs them to get started, as seen in Figure 3.

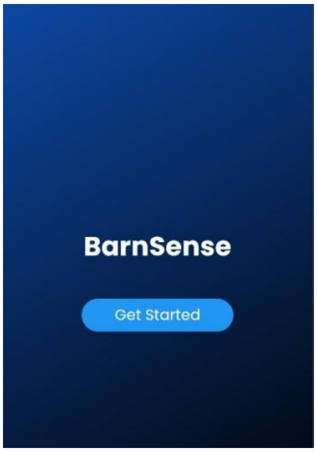

Figure 2. Welcome Page of the App

The system includes a secure user authentication module consisting of a user registration and login page. New users are required to create an account by providing their basic credentials, which are securely stored in the system database. Once registered, users can access the application through the login interface by entering their valid credentials. This authentication mechanism ensures that only authorized users can access the IoT-based tobacco curing system, thereby enhancing data security, user privacy, and controlled system access.

Dashboard Figure 4 central control page offers the following

Current humidity and temperature readings

Status of the system (running or stopped)
Time left for the current stage

Figure 4. Main Dashboard of the App

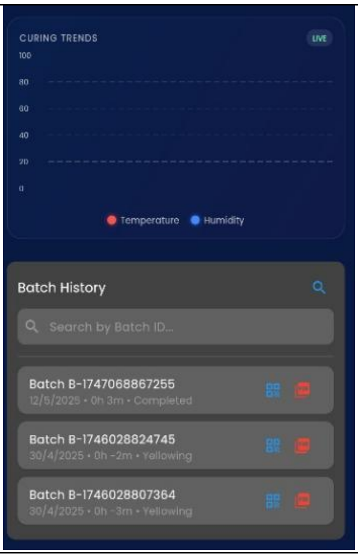

Figure 5. Batch History

Figure 6. Barcode for Batch History

This system's automatic barcode generation for each batch processed is one of its special features. The batch ID, curing date, and stage-by-stage information are encoded in each barcode. This benefits users

For any batch, obtain the complete environmental condition history.
Examine historical performance and refine curing profiles.
Keep up with export or certification documentation and quality control.
Figure 5 and Figure 6 shows the Batch History and Barcode Generation of the system.

Features:

There is no option for manual control in the system created for this project; it only functions in automatic mode. This design decision guarantees a completely autonomous process in which the system automatically controls the tobacco curing environment according to preset humidity and temperature thresholds. There are particular environmental requirements for each of the three curing stages: yellowing, leaf drying, and stem drying. Fan 1 is turned on when the temperature rises above the predetermined limit, Fan 2 is turned on when the temperature drops below the necessary range, and the mist maker is turned on when the humidity deviates from the predetermined threshold. The system continuously monitors the current conditions and reacts appropriately. The system reduces the possibility of human error and ensures a consistent curing process for every batch by doing away with manual intervention. The system makes use of the Firebase SDK for live data synchronization between the mobile application and the hardware in order to facilitate real-time monitoring and control. The Arduino microcontroller uploads the temperature and humidity data to the Firebase Realtime Database after reading it from the sensors. Firebase is integrated with the Flutter-developed mobile application to retrieve and present this data in real time. This guarantees that without requiring a manual refresh, users can view the most recent values for temperature, humidity, the stage of curing, and system status. During the curing process, effective monitoring and precise decision-making are made possible by the smooth communication between hardware and software components. The system also has strong error-handling features to guarantee dependability and fault tolerance. The system is made to stop improper operations and alert the user via the app in situations where sensor readings are absent, null, or outside of expected bounds. Additionally, the mobile application can identify problems with Firebase connectivity and notify the user when data retrieval fails.

To maintain transparency and system integrity, the relevant error messages are shown in the event that any issues arise when commands like Start, Stop, or Reset are being executed, or when batch-specific barcodes are being generated and saved. The automated tobacco curing system's stability and efficacy depend heavily on these error-handling features.

Limitations:

The present work focuses on the design and prototype implementation of an IoT-based tobacco curing management system. The prototype was evaluated under controlled conditions and has not yet undergone large-scale field deployment in commercial tobacco curing barns. Environmental variations, long-term reliability, sensor drift, network disruptions, and seasonal operating conditions were outside the scope of this study. Future research should include extensive field validation and performance benchmarking under real operational environments.

Practical Implications and Scalability:

The suggested IoT-based tobacco curing system provides several practical benefits for tobacco farmers and curing barn operators. By automating temperature and humidity management, the system reduces the need for continuous manual supervision, thereby lowering labor requirements and minimizing human errors during the curing process. The Flutter-based mobile application also enables farmers to monitor the curing conditions in real-time, giving them the ability to remotely observe the curing conditions and respond quickly to operational issues that improve the overall consistency of curing and product quality.

In terms of scalability, the system is constructed with low-cost and commonly available components, such as the ESP32 microcontroller, DHT11 sensor, Firebase Realtime Database and the Flutter framework. Cloud-based architecture allows for simultaneous monitoring and management of multiple curing barns through a central platform, with no considerable changes in the system design. Furthermore, the modular architecture allows for the integration of additional sensors, smart decision-support algorithms and advanced communication technologies in the future. The proposed system is therefore well suited to small, medium and potentially large-scale tobacco curing operations, particularly in developing agricultural areas where low-cost automation solutions are needed.

Recommendations and Future work:

Although the proposed IoT-based tobacco curing system successfully demonstrated the integration of real-time monitoring, automated environmental control, cloud-based data management, and mobile application support, several improvements can be considered for future development and practical deployment.

Future work should focus on large-scale field implementation in commercial tobacco curing barns to evaluate the long-term reliability, stability, and effectiveness of the system under real operating conditions. Such deployments would provide valuable insights into system performance across different environmental conditions, barn sizes, and tobacco curing requirements.

The current prototype utilizes a DHT11 sensor for temperature and humidity monitoring due to its low cost and ease of integration. Future implementations may consider the use of higher-precision industrial-grade sensors to improve measurement accuracy and enhance environmental control performance. In addition, deploying multiple sensors at different locations within the curing barn could provide more comprehensive environmental monitoring and improve control decisions.

Communication reliability is another important consideration for practical deployment. Since the current system relies on Wi-Fi connectivity and cloud synchronization through Firebase, network interruptions may affect real-time data transmission. Future versions of the system may incorporate alternative communication technologies such as

GSM, LoRaWAN, or hybrid communication architectures to improve reliability in rural areas where internet connectivity may be limited or unstable.

The proposed system can also be enhanced through the integration of artificial intelligence and machine learning techniques. Historical temperature, humidity, and operational data can be analyzed to develop predictive models capable of forecasting environmental changes and automatically optimizing actuator operations. Such intelligent decision-support mechanisms may further improve curing consistency and operational efficiency.

Additional future enhancements may include energy optimization strategies, predictive maintenance features for connected devices, automated fault detection mechanisms, and integration with broader smart agriculture platforms. These improvements would increase system scalability, sustainability, and suitability for adoption in modern agricultural environments.

Overall, the proposed system provides a foundation for the development of intelligent tobacco curing solutions, and future research should focus on advanced automation, large-scale validation, and intelligent decision-making capabilities to further enhance its practical applicability.

Results & Discussions:

The results and analysis of BarnSense, an Internet of Things-based tobacco curing system that automates and optimizes the tobacco curing process through real-time temperature and humidity monitoring, are presented in this chapter. The system has barcode-based batch tracking, stage-based environment control, automated fan and mist maker control, and Firebase integration. This chapter assesses the system's functionality, effectiveness, and constraints while pinpointing areas in need of development. Throughout the three curing stages yellowing, leaf drying, and stem drying the system exhibits dependable and real-time temperature and humidity monitoring and control within the curing barn. Based on sensor data, it automatically modifies fan and mist maker operations to maintain ideal environmental conditions. The mobile app offers users live updates, system control options, batch tracking via barcode generation, and precise data transmission to Firebase with little delay. Under normal curing conditions, the system works effectively and drastically cuts down on the amount of manual intervention required, which enhances curing consistency and tobacco quality overall.

Stagewise Environmental Targets and System Response Time:

The automated tobacco curing system's time response and stage-by-stage accuracy are shown in Table 3. Three separate phases make up the curing process yellowing, leaf drying, and stem drying. To guarantee ideal curing conditions, each stage is linked to particular target ranges for temperature and humidity. All things considered, this table demonstrates how quickly and precisely the system can adapt to the desired environmental conditions during each curing stage. The proposed IoT-based control algorithm was evaluated using a prototype under controlled conditions. The observed accuracy levels and response times indicate the system capability to regulate the critical environmental parameters required for tobacco curing. Table 3 presents Stagewise Environmental Targets and System Response Time

Table 3. Stagewise Environmental Targets and System Response Time

Stage	Target Temp (°C)	Target Humidity (%)	Response Time (s)
Yellowing	25-26	85-90	2
Leaf Drying	28-30	60-70	2
Stem Drying	31-32	10-15	2

Firebase Data Logging:

Every sensor value and actuator state is instantly recorded in Firebase. Batch tracking and result retrieval are made possible by the unique barcode ID that is connected to each curing session. The following parameters are stored in Firebase:

Timestamp

The temperature

The level of humidity

System status (ON/OFF)

Comparison with Traditional Method:

A comparison of the suggested BarnSense IoT-based system and the conventional manual tobacco curing method is shown in Table 4, with significant gains in data management, automation, accuracy, and labor efficiency. Human error and inconsistencies may result from the manual method's requirement that the operator manually monitor and modify the environment at each curing stage during stage transitions. By switching between phases according to predetermined time frames, the BarnSense system automates this procedure, guaranteeing consistency and lowering the need for human oversight. The IoT system also drastically lowers labor requirements. While the traditional approach requires skilled workers to be present and intervene constantly, BarnSense allows for remote monitoring and control through a mobile application, requiring less labor.

Regarding data logging, there is no systematic way to record temperature and humidity data using the manual approach. Better tracking, analysis, and historical reference are made possible by the BarnSense system's automatic logging of all environmental data to Firebase. Lastly, manual operations lack batch tracking, which makes it challenging to link particular curing results to prior environmental circumstances. In order to solve this, BarnSense has put in place a barcode system that creates a distinct barcode for every batch, allowing users to access and examine the information from any previous curing cycle. This comparison makes it abundantly evident that the BarnSense system outperforms the conventional curing techniques in terms of efficiency, accuracy, consistency, and data management. The comparison with the manual system is presented in Table 4.

Table 4. Comparison Table with manual system

Feature	Manual Curing	BarnSense IoT System
Stage Transition	Manual	Automatic (based on time)
Labor Requirement	High	Low
Data Logging	None	Automated Firebase
Batch Tracking	Not Available	Barcode System

Conclusion:

This IoT-based system was successfully developed for controlling temperature and humidity in tobacco curing barns in Pakistan. This system automates environmental conditions during the curing process with sensors along with automated control mechanisms. Firebase is used for cloud-based data storage, while a flutter mobile application provides real-time monitoring and control features such as Start, Stop, and Reset. A barcode generation feature is integrated to enable the batch-wise tracking and retrieval of curing data. Overall, the system improved the curing efficiency, reduced manual effort and provided real-time performance through the integration of IoT Hardware, Firebase and Flutter. Future work will focus in improving functionality, scalability and automation through the integration of AI and machine learning Techniques. Predictive algorithm will be used to analyze the historical data and automatically adjust temperature and humidity level before environmental changes occur.

Acknowledgement: None

Author's Contribution: TJ, HH, SSK, and MU: Conceptualization, Methodology, Formal analysis, Investigation. TJ, and HH: Writing—original draft preparation, Validation. MU and SSK: Supervision, MU, and SSK: Writing—review and editing. All authors reviewed the results and approved the final version of the manuscript.

Conflict of interest: The authors declare no conflict of interest to report regarding the present study.

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