
Design and Implementation of a Smart IoT-Based Seed Germination Chamber with Remote Monitoring and Predictive Control

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Abstract: Seed germination is a critical stage in agricultural production that requires precise environmental control to ensure optimal growth conditions. This paper presents the design and implementation of a smart Internet of Things (IoT) based seed germination chamber with remote monitoring and predictive control. The proposed system integrates temperature, humidity, and soil moisture sensors with a microcontroller-based control system to maintain optimal environmental conditions automatically. The system uses IoT technology for real-time monitoring and remote control through a cloud platform. A predictive control algorithm is implemented to analyze environmental data and adjust irrigation, lighting, and ventilation systems accordingly. Experimental results demonstrate that the proposed system improves germination efficiency, reduces water consumption, and minimizes manual intervention. The system provides a low-cost and efficient solution for smart agriculture and controlled environment farming.

Keywords: IoT, Smart Agriculture, Seed Germination, Predictive Control, Environmental Monitoring, Automation.

1. Introduction

Agriculture remains one of the most important sectors for ensuring global food [1] security, economic sustainability, and rural development. With the rapid growth of the global population and increasing demand for food production, modern agriculture is shifting toward automation and precision farming technologies. One of the most critical stages in crop production is seed germination [2], as it directly affects plant growth, crop yield and overall agricultural productivity. Successful seed germination depends on maintaining optimal environmental conditions such as temperature, humidity, soil moisture, and light intensity. Any imbalance in these environmental parameters can significantly reduce germination rates and negatively impact seedling development.

Traditional seed germination methods [3] rely on manual monitoring and environmental conditions, which often result in inconsistent growth environments. Manual irrigation, uncontrolled temperature, and irregular humidity levels can lead to poor germination rates, water wastage, and increased labor costs. In many agricultural practices, farmers are unable to continuously monitor environmental conditions, which leads to inefficient resource management [4] and reduced agricultural efficiency. Therefore, there is a growing need for automated systems that can monitor and control environmental conditions in real time. Recent advancements in embedded systems, wireless communication, and the Internet of Things (IoT) have enabled the development of smart agricultural [5] systems that can monitor environmental conditions and automatically control irrigation and climate parameters. IoT-based agricultural systems use sensors to collect environmental data [6] and transmit the data to cloud platforms for monitoring and analysis. These systems allow farmers and researchers to monitor agricultural

environments remotely using smartphones or computers. Automation and remote monitoring reduce human effort, improve system efficiency, and ensure optimal [7] environmental conditions for plant growth.

A seed germination chamber is a controlled environment system designed to maintain optimal conditions required for seed germination and early plant growth. The key environmental parameters [8] that influence seed germination include temperature, relative humidity, soil moisture, and light exposure. Maintaining these parameters within specific ranges significantly improves germination speed, germination percentage, and seedling quality. However, maintaining these environmental conditions manually is difficult and inefficient, especially in large-scale agricultural applications or research laboratories.



Figure 1. Seed germination chamber

The proposed system integrates multiple environmental [9] sensors, including temperature, humidity, and soil moisture sensors, with a microcontroller-based control system. The system automatically controls irrigation, lighting, and ventilation systems based on real-time sensor data. The integration of IoT technology allows users to monitor environmental parameters remotely and control the system from anywhere using a mobile or web application.

To real-time monitoring and automatic control, the proposed system incorporates a predictive control algorithm. Predictive control [10] is an advanced control technique that uses previous sensor data and environmental trends to predict future environmental conditions and take control actions in advance. This approach reduces environmental fluctuations, improves system stability, reduces energy consumption, and ensures optimal conditions for seed germination. The predictive control system helps maintain stable environmental parameters, which is essential for achieving uniform seed germination and healthy seedling growth.

The proposed system provides a sustainable and efficient solution for smart agriculture, greenhouse farming, plant research laboratories, and controlled environment agriculture. The system is low-cost, easy to implement, and suitable for small-scale farmers as well as research applications. The integration of IoT and predictive control [11] makes the system more efficient and reliable compared to traditional germination systems.

2. Literature Review

The application of IoT technology in agriculture has gained significant attention in recent years due to its ability to enable real-time monitoring, automation, and efficient resource management. Smart agriculture systems integrate sensors, wireless communication, and automated control systems to improve crop productivity and reduce water and energy consumption. Wolfert et al. [12] discussed the role of big data and IoT in smart farming and showed how data-driven agriculture improves productivity, resource management, and decision-making in modern agriculture.

IoT-based irrigation systems are widely used to monitor soil moisture and automatically control irrigation systems. These systems use soil moisture sensors to detect the water content in soil and activate irrigation when the moisture level drops below a predefined threshold. Automated irrigation systems significantly reduce water wastage and improve irrigation efficiency. Saraf et al. [13] developed an IoT-based irrigation monitoring and control system that automatically controls irrigation based on soil moisture levels. Similarly, Kumar et al. [14] developed a low-cost soil moisture monitoring system using Arduino for automated irrigation applications.

Wireless Sensor Networks (WSN) have also been used in smart agriculture for environmental monitoring. These systems consist

of distributed sensor nodes that collect environmental data such as temperature, humidity, soil moisture, and light intensity. The collected data is transmitted to a central server for monitoring and analysis. Kim et al. [15] developed a wireless sensor network-based irrigation monitoring system for remote sensing and control of irrigation systems. Ndunagu et al. [16] developed a wireless sensor network and IoT-based smart irrigation system for agricultural monitoring.

Greenhouse automation systems have been developed to maintain environmental conditions using automated fans, heaters, irrigation systems, and lighting systems. These systems improve plant growth by maintaining controlled environmental conditions. Navarro-Hellín et al. [17] developed a decision support system for irrigation management that helps optimize water usage and improve agricultural efficiency. García et al. [18] presented an IoT-based smart irrigation system that integrates sensors and IoT communication for precision agriculture applications.

Recent research has introduced predictive control techniques and intelligent monitoring systems in smart agriculture. Predictive control systems analyze environmental data and automatically adjust system parameters to maintain optimal environmental conditions. Sanjeevi et al. [19] proposed an IoT-based precision agriculture system that uses intelligent control techniques for improving agricultural productivity. Adhikary et al. [20] developed a real-time soil nutrient monitoring system using Nitrogen (N), Phosphorus (P) and Potassium (K) (NPK) sensors for precision agriculture applications.

Automation in irrigation canal systems has also been studied to improve water distribution efficiency. Shingote et al. [21] developed a microcontroller-based canal gate control system for irrigation canal automation. Ultrasonic sensors are widely used for water level measurement in irrigation systems. Kumar et al. [22] evaluated the performance of ultrasonic sensors for open channel water level measurement.

Although many IoT-based agricultural monitoring systems have been developed, most existing systems focus only on irrigation or environmental monitoring separately and lack predictive control and integrated environmental control systems specifically designed for seed germination chambers. Vallejo-Gomez et al. [23] conducted a systematic review of smart irrigation systems and concluded that integrated monitoring and control systems are required for improving agricultural efficiency and sustainability. Therefore, this research proposes an IoT-based seed germination chamber with predictive control and remote monitoring to ensure optimal environmental conditions for seed germination and early plant growth.

From the literature review, it is observed that most existing IoT-based agricultural systems focus on irrigation automation and environmental monitoring separately. However, limited research has been conducted on integrated seed germination chamber systems that combine temperature, humidity, and soil moisture control with predictive control and remote monitoring. Furthermore, many existing systems use simple threshold-based control, which may lead to environmental fluctuations and inefficient resource utilization. Therefore, there is a need for a predictive control-based IoT system that can maintain stable environmental conditions for seed germination. This research aims to develop a low-cost IoT-based seed germination chamber with predictive control and remote monitoring capabilities.

3. System Architecture

3.1. System Overview

A Smart IoT-Based Seed Germination Chamber [24] is designed to maintain optimal environmental conditions required for seed germination through real-time monitoring, automated control, and intelligent decision-making. Seed germination is highly sensitive to factors such as temperature, humidity, soil moisture, and light intensity. Variations in these parameters can significantly affect germination rate, seedling growth, and overall plant health. Maintaining a stable and controlled environment is therefore essential for improving germination efficiency and plant development. To address this need, the proposed system integrates environmental sensors, a microcontroller-based processing unit, control devices, and an IoT-based remote monitoring platform into a unified automated system.

Continuous monitoring of environmental parameters is achieved through multiple sensors installed inside the germination chamber. Data collected from these sensors is transmitted to the processing unit, where the microcontroller analyzes and compares it with predefined optimal conditions. Based on this comparison, actuators such as the irrigation pump, exhaust fan, and lighting system are activated or deactivated to maintain desired conditions. This automation reduces manual intervention and ensures that environmental parameters remain within the optimal range for seed germination.

A closed-loop feedback control structure governs the overall operation of the system. In this mechanism, sensor data serves as the feedback signal, while predefined environmental conditions act as the reference input. The microcontroller continuously calculates the difference between these values, known as the error signal. Appropriate control actions are then generated to minimize this error and maintain environmental stability. Compared to traditional manual systems, this approach enhances accuracy, response time, and reliability.

Four main functional units form the system architecture: the sensing unit, processing unit, control unit, and IoT monitoring unit. Environmental data such as temperature, humidity, and soil moisture is collected by the sensing unit. Analysis and decision-making are handled by the processing unit using control algorithms. Regulation of environmental conditions is performed by the control unit through actuators. Remote monitoring and control are enabled by the IoT monitoring unit via a cloud platform, allowing users to access real-time data from any location.

Integration of IoT technology with automated environmental control significantly enhances efficiency, flexibility, and user

convenience. Beyond real-time monitoring, the IoT platform stores environmental data for future analysis. This stored data can support predictive control, enabling the system to anticipate environmental changes and respond proactively. As a result, the system offers a smart, automated, and efficient solution for seed germination and controlled environment agriculture.

A block diagram of the Smart IoT-Based Seed Germination Chamber highlights four primary sections: the sensing unit, processing unit, control unit, and IoT monitoring unit. These components are interconnected in a closed-loop feedback system to maintain optimal environmental conditions for seed germination.

Included in the sensing unit are temperature and humidity sensors (DHT11), a soil moisture sensor, and a light sensor. These devices continuously measure environmental parameters inside the chamber and transmit data to the processing unit, functioning as the feedback element of the control system.

At the core of the processing unit is the NodeMCU (ESP8266) microcontroller, which serves as the system's central controller. It reads and processes sensor data, compares measured values with predefined set points, and generates control signals accordingly. Additionally, it transmits real-time data to the IoT cloud platform via Wi-Fi for remote monitoring.

Comprising the control unit are relay modules, a water pump, an exhaust fan, and a heating bulb (light source). Acting as switching devices, the relay modules enable the microcontroller to control high-voltage components. For instance, the water pump is activated when soil moisture is low, the exhaust fan operates when temperature rises, and the heating bulb turns on when temperature drops.

Functioning as the IoT monitoring unit are a cloud server and a mobile or web application. Real-time sensor data is transmitted by the NodeMCU to the cloud platform, allowing users to monitor environmental conditions remotely. Users can also send control commands through the application to manage the system from a distance.

So, system operation relies on a closed-loop control mechanism where sensors continuously monitor environmental conditions, the controller processes incoming data, and actuators adjust the environment accordingly. This approach ensures that temperature, humidity, and soil moisture remain within the optimal range required for efficient seed germination.

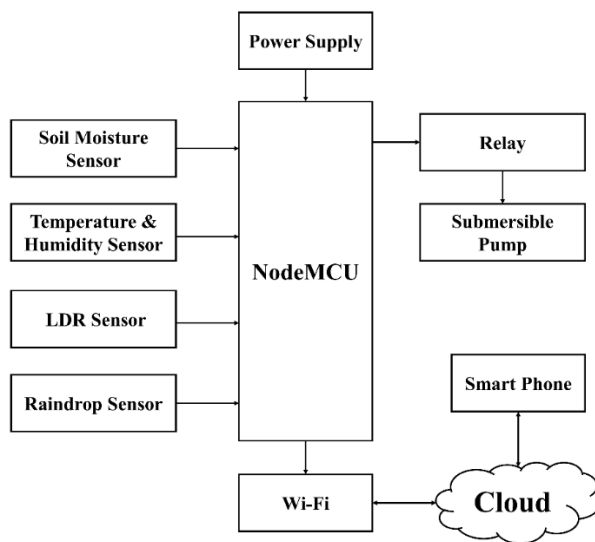


Figure 2. Block representation of the smart IoT-based seed germination chamber

3.2. Sensing Unit

The sensing unit is responsible for collecting real-time environmental data from the germination chamber. Multiple sensors are used to monitor environmental parameters that directly affect seed germination and plant growth. The soil moisture sensor is used to measure the water content present in the soil. The sensor operates by detecting changes in soil conductivity and sends analog signals to the microcontroller, which helps determine whether irrigation is required. The temperature and humidity sensor (DHT11) is used to measure the temperature and relative humidity inside the germination chamber. Temperature and humidity are critical parameters for seed germination, and maintaining these parameters within a specific range improves germination efficiency and seedling growth. The sensing unit continuously collects environmental data and sends the data to the processing unit for analysis and decision-making.

3.3. Processing Unit

The processing unit is the central part of the system and is implemented using the NodeMCU (ESP8266) microcontroller. The NodeMCU collects data from all sensors, processes the data, and makes control decisions based on predefined threshold values and predictive control algorithms. The microcontroller reads sensor data such as temperature, humidity, and soil moisture,

compares the sensor values with predefined threshold values, and executes the control algorithm accordingly. The processing unit then sends control signals to actuators such as the water pump, exhaust fan, and lighting system. In addition, the NodeMCU uploads sensor data to the IoT platform via Wireless Fidelity (Wi-Fi) and displays system status on the Liquid Crystal Display (LCD). The NodeMCU microcontroller is selected for this system because it has built-in Wi-Fi capability, which allows direct communication with the IoT cloud platform for remote monitoring and control

3.4. Control Unit

The control unit consists of actuators such as a water pump, exhaust fan, and lighting system, which are controlled through relay modules. The control unit receives control signals from the microcontroller and performs necessary actions to maintain optimal environmental conditions inside the germination chamber. The control mechanism operates based on sensor readings and predefined threshold values. If the soil moisture level falls below the threshold value, the microcontroller activates the water pump to irrigate the soil. If the temperature exceeds the predefined limit, the exhaust fan is activated to reduce the temperature inside the chamber. If the temperature falls below the desired level, the bulb or heating source is activated to increase the temperature. The relay module acts as an interface between the microcontroller and high-power electrical devices. This automated control system helps maintain environmental stability inside the germination chamber and ensures optimal conditions for seed germination.

3.5. IoT Monitoring Unit

The IoT monitoring unit enables remote monitoring and control of the system through the internet. The NodeMCU sends sensor data to a cloud platform via Wi-Fi, allowing users to monitor environmental parameters such as temperature, humidity, and soil moisture in real time using a mobile application or web dashboard. The IoT platform provides several features, including real-time environmental monitoring, remote control of irrigation and ventilation systems, data storage and analysis, alert notifications for abnormal environmental conditions, and predictive analysis for environmental control. This remote monitoring capability allows users to monitor and control the germination chamber from any location, which improves system flexibility, usability, and efficiency.

3.6. Closed-Loop Control Operation

The proposed system operates based on a closed-loop feedback control system. In this system, environmental parameters are continuously monitored by sensors and compared with predefined reference values stored in the microcontroller. The microcontroller calculates the error between the measured value and the desired value and generates control signals to actuators to minimize the error. The closed-loop control process can be expressed as:

$$\text{Error} = \text{Desired Value} - \text{Measured Value}$$

$$\text{Control Action} = f(\text{Error})$$

Where the control action activates irrigation, heating, or cooling systems to maintain environmental stability. This closed-loop feedback control system improves system accuracy, stability, and efficiency compared to manual control systems. The system continuously repeats this process, ensuring that environmental conditions remain within the desired range for optimal seed germination and plant growth.

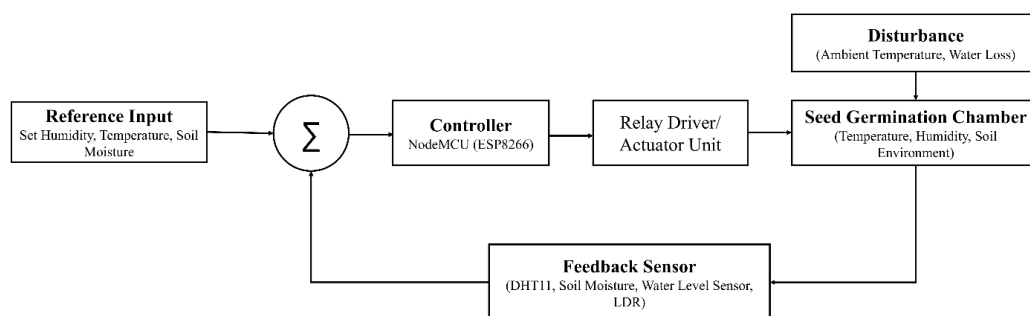


Figure 3. Closed-loop control block diagram of the smart IoT-Based seed germination chamber showing reference input, controller, actuator unit, plant, feedback sensors and disturbance

The control block diagram represents a closed-loop feedback control system in which environmental parameters such as temperature, humidity, and soil moisture are continuously monitored and controlled. The reference input represents the desired environmental conditions, while the sensors provide feedback signals representing the actual environmental conditions. The controller processes the error between the desired and measured values and generates control signals to actuators such as the irrigation pump, exhaust fan, and heating bulb. The actuators adjust environmental conditions inside the germination chamber. External disturbances such as ambient temperature and water loss affect the system, but the closed-loop control system

compensates for these disturbances and maintains environmental stability.

4. Mathematical Model of the System

4.1. System Modeling Overview

The proposed Smart IoT-Based Seed Germination Chamber operates as a closed-loop control system in which environmental parameters such as temperature, humidity, and soil moisture are continuously monitored and controlled. The mathematical model of the system is developed to describe the relationship between environmental parameters, sensor measurements, and control actions. The control system aims to maintain environmental parameters at predefined optimal levels required for seed germination.

Let the desired environmental parameters be defined as reference inputs, and the measured environmental parameters be defined as feedback signals. The control system calculates the error between the desired value and the measured value and generates control actions to minimize the error.

The general control system relationship is expressed as

$$e(t) = r(t) - y(t)$$

where $e(t)$ denotes the error signal, $r(t)$ represents the reference (desired) value, and $y(t)$ is the measured environmental parameter. The control action is formulated as a function of this error signal and is defined by $u(t) = K e(t)$, where $u(t)$ is the control signal and K denotes the control gain.

4.2. Temperature Control Model

Temperature inside the germination chamber is regulated using a heating element (bulb) and an exhaust fan. The thermal behavior of the chamber can be modeled as a first-order system expressed by

$$\frac{dT(t)}{dt} = -a(T(t) - T_{env}) + b \cdot u_T(t)$$

where $T(t)$ denotes the chamber temperature, T_{env} is the ambient temperature, $u_T(t)$ represents the control input from the heater and fan, a is the heat-loss coefficient, and b is the heating coefficient.

The temperature error is defined as

$$e_T(t) = T_{set} - T(t)$$

where T_{set} is the desired temperature. Accordingly, the control action is formulated as $u_T(t) = K_T e_T(t)$, where K_T denotes the temperature control gain.

4.3. Soil Moisture Control Model

Soil moisture within the germination chamber is regulated using an irrigation pump. The moisture dynamics can be modeled as a first-order system described by

$$\frac{dM(t)}{dt} = -c \cdot M(t) + d \cdot u_M(t)$$

where $M(t)$ represents the soil moisture level, $u_M(t)$ is the irrigation control input corresponding to the pump operation, c is the moisture evaporation coefficient, and d is the irrigation coefficient.

The moisture error is defined as

$$e_M(t) = M_{set} - M(t)$$

where M_{set} denotes the desired soil moisture level. The corresponding control action is expressed as

$$u_M(t) = K_M e_M(t)$$

where K_M is the moisture control gain.

4.4. Humidity Control Model

Humidity inside the germination chamber is influenced by temperature and water evaporation. The humidity dynamics can be modeled as a first-order system given by

$$\frac{dH(t)}{dt} = -e \cdot H(t) + f \cdot u_H(t)$$

where $H(t)$ denotes the humidity level, $u_H(t)$ represents the humidity control input, e is the humidity loss coefficient, and f is the humidity control coefficient.

The humidity error is defined as

$$e_H(t) = H_{set} - H(t)$$

where H_{set} is the desired humidity level. The corresponding control action is expressed as

$$u_H(t) = K_H e_H(t)$$

where K_H denotes the humidity control gain.

4.5. Overall Control Model

The overall control system integrates temperature, humidity, and soil moisture regulation into a unified control action expressed as

$$u(t) = K_T e_T(t) + K_M e_M(t) + K_H e_H(t)$$

where $e_T(t)$, $e_M(t)$, and $e_H(t)$ represent the temperature, soil moisture, and humidity error signals, respectively. This formulation represents the combined control effort required to maintain optimal environmental conditions inside the germination chamber.

5. Control Algorithm

5.1. Overview of Control Algorithm

The control algorithm is responsible for maintaining optimal environmental conditions inside the seed germination chamber by controlling temperature, humidity, soil moisture, and light intensity. The proposed system uses a closed-loop feedback control algorithm in which sensor data is continuously monitored and compared with predefined reference values. Based on the error between the measured value and the desired value, the controller generates control signals to activate or deactivate actuators such as the irrigation pump, exhaust fan, and heating bulb.

The control algorithm operates in a continuous loop, where environmental data is collected, processed, and control decisions are made automatically. The algorithm ensures that environmental parameters remain within the desired range required for optimal seed germination and plant growth.

5.2. Control Logic

The control logic of the system is based on threshold values and error control. The algorithm continuously reads sensor data and compares it with predefined set values.

The control logic can be summarized as follows:

- If soil moisture is below the set value, the irrigation pump is turned ON.
- If soil moisture reaches the desired level, the irrigation pump is turned OFF.
- If temperature is higher than the set value, the exhaust fan is turned ON.
- If temperature is lower than the set value, the heating bulb is turned ON.
- If temperature returns to the desired range, both fan and bulb are turned OFF.
- If humidity is below the desired level, irrigation or humidity control is activated.
- Sensor data is continuously sent to the IoT platform for monitoring.
- The system repeats this process continuously.

This control mechanism ensures stable environmental conditions inside the germination chamber.

5.3. Control Algorithm Flow

The flowchart of the Smart IoT-Based Seed Germination Chamber describes the sequential operation of the system. The system begins by initializing the microcontroller and sensors. After initialization, the system reads environmental data from the temperature, humidity, and soil moisture sensors. The sensor data is then compared with predefined set values stored in the microcontroller.

If the soil moisture level is below the set value, the irrigation pump is activated to supply water to the soil. If the soil moisture level reaches the desired value, the pump is turned off automatically. Similarly, if the temperature is higher than the set value, the exhaust fan is activated to reduce the temperature inside the chamber. If the temperature is lower than the set value, the

heating bulb is activated to increase the temperature.

After taking the necessary control actions, the system sends sensor data to the IoT cloud platform for remote monitoring. The system then waits for a short delay and repeats the entire process. This continuous loop represents the closed-loop control operation of the system.

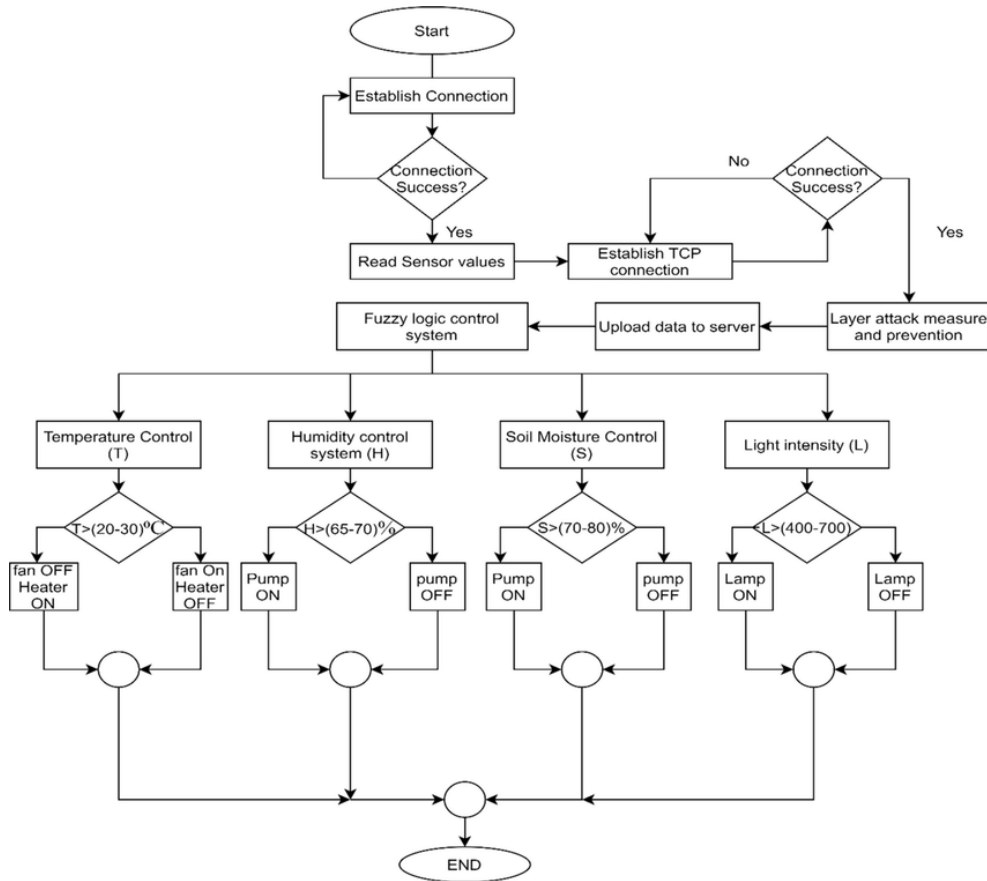


Figure 4. Flowchart of the smart IoT-based seed germination chamber control algorithm.

5.4. Control Algorithm Equation

The control algorithm can be expressed mathematically as:

$$u(t) = \begin{cases} \text{Pump ON,} & \text{if } M(t) < M_{set} \\ \text{Fan ON,} & \text{if } T(t) > T_{set} \\ \text{Heater ON,} & \text{if } T(t) < T_{set} \\ \text{System OFF,} & \text{if } T = T_{set}, M = M_{set} \end{cases}$$

The control algorithm can be mathematically described using a rule-based switching strategy based on environmental conditions. The control input $u(t)$ activates the irrigation pump when $M(t) < M_{set}$, operates the fan when $T(t) > T_{set}$, and turns on the heater when $T(t) < T_{set}$. The system remains OFF when both temperature and soil moisture reach their desired setpoints, i.e., $T(t) = T_{set}$ and $M(t) = M_{set}$. Here, $T(t)$ and $M(t)$ represent the real-time temperature and soil moisture levels, while T_{set} and M_{set} denote their respective desired reference values.

5.5. Predictive Control Extension

To enhance system performance, predictive control is incorporated into the proposed system. The predictive control algorithm utilizes historical sensor data to forecast future environmental conditions and initiates appropriate control actions in advance. The prediction model is expressed as

$$X(t + 1) = X(t) + \alpha(X(t) - X(t - 1))$$

where $X(t)$ represents the current sensor value, $X(t - 1)$ is the previous sensor reading, $X(t + 1)$ denotes the predicted future value, and α is the prediction constant. This predictive control approach helps to reduce environmental fluctuations and

improves overall system stability and response performance.

6. Experimental Results and Discussion

6.1 Experimental Setup

The Smart IoT-Based Seed Germination Chamber was tested to evaluate its performance in maintaining optimal environmental conditions for seed germination. The system monitored temperature, humidity, and soil moisture in real time and controlled irrigation, heating, and ventilation automatically based on predefined set values. The experiment was conducted over several days, and sensor data was recorded at regular intervals to analyze system performance and environmental stability.

The predefined environmental conditions for seed germination were set as follows:

Table 1. Parameter and set values for environmental condition

Parameter	Set Value
Temperature	28°C
Humidity	70%
Soil Moisture	60%

The system continuously monitored environmental parameters and activated control devices when the measured values deviated from the set values.

6.2 Experimental Data Table

Table below shows the recorded environmental data and system response during the experiment

Table 1. The recorded environmental data and system responses during the experiment.

Time (min)	Temperature (°C)	Humidity (%)	Soil Moisture (%)	Pump Status	Fan Status	Light Status
0	25	60	45	ON	OFF	ON
10	26	63	50	ON	OFF	ON
20	27	65	55	ON	OFF	OFF
30	28	68	60	OFF	OFF	OFF
40	29	72	62	OFF	ON	OFF
50	28	70	61	OFF	OFF	OFF
60	28	70	60	OFF	OFF	OFF

6.3. System Performance Analysis

From the experimental results, it is observed that the system successfully maintained environmental conditions within the desired range. Initially, the soil moisture level was below the set value, so the irrigation pump was activated automatically. As the soil moisture reached the desired level, the pump was turned off automatically, which prevented over-irrigation and water wastage. Similarly, when the temperature increased above the set value, the exhaust fan was activated to reduce the temperature inside the chamber. When the temperature returned to the desired range, the fan was turned off automatically. The heating bulb was used when the temperature was below the desired level.

The results show that the closed-loop control system responded effectively to environmental changes and maintained stable environmental conditions for seed germination.

The temperature variation over time is shown in Fig. 5. Initially, the temperature inside the chamber was below the desired set value. The heating system was activated to increase the temperature. When the temperature exceeded the set value, the exhaust fan was activated to reduce the temperature. The graph shows that the control system successfully maintained the temperature around the desired value of 28°C, demonstrating the effectiveness of the closed-loop temperature control system.

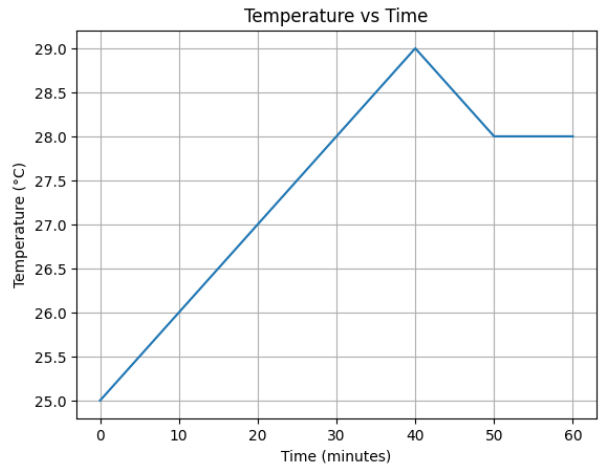


Figure 5. Temperature vs Time showing temperature stabilization using automatic control system

The soil moisture variation over time is shown in Fig. 6. Initially, the soil moisture level was below the desired level, and the irrigation pump was activated automatically. As the soil moisture reached the set value, the pump was turned off. The graph shows that the system-maintained soil moisture around the desired value of 60%, which confirms the proper operation of the automatic irrigation control system

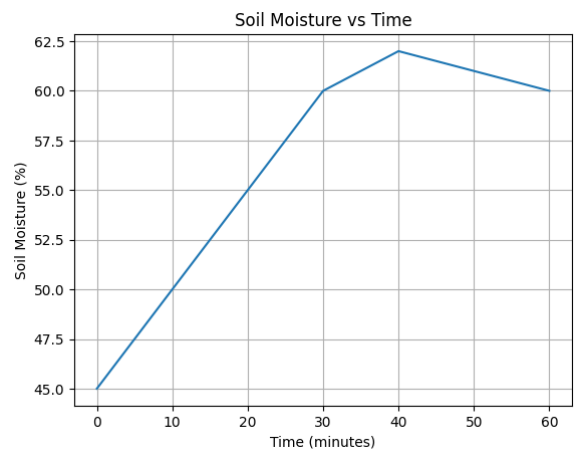


Figure 6. Soil Moisture vs Time showing automatic irrigation control

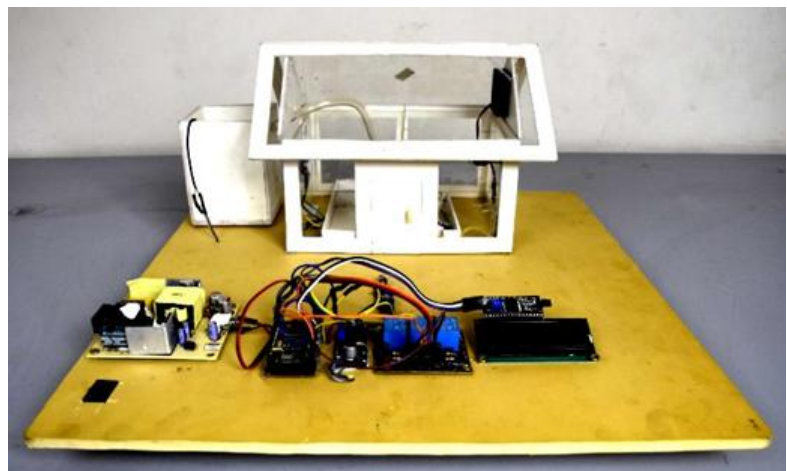


Figure 7. Final Implemented Circuit

6.4. Discussion

The proposed Smart IoT-Based Seed Germination Chamber demonstrated efficient performance in maintaining environmental

stability compared to manual monitoring systems. The automated irrigation system reduced water usage by supplying water only when soil moisture was below the required level. The temperature control system maintained stable temperature conditions using the exhaust fan and heating bulb.

The integration of IoT technology allowed real-time monitoring and remote control of the system, which improved system flexibility and usability. The predictive control algorithm helped reduce environmental fluctuations by predicting environmental changes and taking control actions in advance.

The experimental results indicate that the proposed system improves germination conditions, reduces manual labor, and ensures efficient resource utilization. The system is suitable for greenhouse farming, research laboratories, and smart agriculture applications.

6.5 Conclusion

This paper presented the design and implementation of a Smart IoT-Based Seed Germination Chamber with Remote Monitoring and Predictive Control. The proposed system was developed to maintain optimal environmental conditions required for seed germination by monitoring and controlling temperature, humidity, and soil moisture using sensors, a microcontroller, and automated control devices. The system operates based on a closed-loop feedback control mechanism in which environmental parameters are continuously monitored and compared with predefined reference values, and control actions are taken automatically to maintain environmental stability.

The integration of IoT technology enables real-time monitoring and remote control of the germination chamber through a cloud platform, which reduces manual labor and improves system efficiency. The predictive control algorithm further enhances system performance by predicting environmental changes and taking control actions in advance to prevent environmental fluctuations. This improves system stability and ensures a suitable environment for seed germination and early plant growth.

The experimental results demonstrate that the proposed system can maintain temperature, humidity, and soil moisture within the desired range. The automated irrigation system reduces water consumption by supplying water only when required, while the automated temperature control system maintains stable temperature conditions inside the chamber. The system also provides real-time monitoring and data logging, which can be used for future analysis and agricultural research.

The proposed system offers several advantages, including low cost, energy efficiency, reduced human intervention, efficient water management, and improved germination conditions. The system can be used in smart agriculture, greenhouse farming, plant research laboratories, and controlled environment agriculture. The results indicate that the proposed Smart IoT-Based Seed Germination Chamber is an effective and reliable solution for automated seed germination and environmental monitoring.

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