Design of environmental monitoring and control system in climatic chamber for True Shallot Seed (TSS) seedlings based on the internet of things

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Abstract. The microclimate and environmental conditions during the shallot seedling stage significantly influence growth quality. Therefore, a robust monitoring and control system within the climatic chamber is essential to ensure optimal conditions and adjust parameters throughout the cultivation process. This study aims to develop a system for monitoring and controlling the climatic chamber environment and to evaluate the performance of the implemented system. The research involved several stages: system analysis, design, testing, and performance evaluation. The electronic components and sensors include DHT21, DS18B20, BH1750, ESP8266 microcontroller, and 4-channel relays. The monitoring results show that the climatic chamber's temperature ranged from 20.25–22.79 °C ± 0.64, the humidity level was 77.66–89.31% ± 2.11, and LED light intensity was 2800–2900 lux ± 10.55. The monitoring system was successfully designed using the Blynk Internet of Things (IoT) application to track environmental parameters in the automated climatic chamber. The control system was also developed using the millis syntax and the net time protocol (NTP) module in the Arduino IDE, enabling parameter control based on scheduled on/off durations.

1 Introduction

Shallot (*Allium cepa L.*) is a fundamental horticultural commodity, widely used in culinary practices, and valued for its medicinal properties. In Indonesia, shallot cultivation primarily relies on practical vegetative propagation using bulbs. However, this traditional method has inherent limitations, including restricted genetic improvement and increased susceptibility to pathogens. Over multiple cycles, reliance on the bulbs as seeds accumulate pathogens, reducing seed quality and productivity. Additionally, the dormancy period of bulbs necessitates prolonged storage, further constraining their availability for year-round farming [1]. In contrast, generative propagation using True Shallot Seeds (TSS) derived from

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botanical shallot flowers presents a promising alternative to mitigate these challenges. TSS provides several advantages over traditional bulbs, such as higher productivity, reduced pathogen transmission, and cost efficiency. Moreover, TSS is easier to store and transport and offers an extended shelf life than bulbs. Despite these advantages, the adoption of TSS in Indonesia remains limited, primarily due to the lack of infrastructure and technical support for efficient seedling stages.

The seedling process of TSS by farmers often occurs in open fields, where environmental factors such as temperature, humidity, and light intensity are uncontrollable. Such conditions expose seedlings to abiotic stress and pests, reducing productivity [2]. Controlled environment agriculture (CEA) offers a viable solution by allowing precise regulation of environmental parameters. Plant factories and hydroponic systems enable year-round cultivation and have demonstrated significant potential in overcoming environmental challenges. However, these systems are capital-intensive and often inaccessible to small-scale farmers in developing countries.

In this context, micro-controlled environment systems using climatic chambers tailored for constrained settings are essential to maximize the benefits of TSS seedlings. Aeroponic systems deliver nutrient-rich mist directly to plant roots and are particularly suitable for the fertigation system. Aeroponics enhances oxygen and nutrient uptake, creating optimal root zone conditions for accelerated plant growth. Furthermore, coupling the CEA climatic chamber with the Internet of Things (IoT) can provide real-time monitoring and control of key environmental parameters, ensuring optimal conditions throughout the seedling development cycle [3]. Integrating IoT devices, such as ESP8266 microcontrollers and various sensors, enables efficient data collection and precise environmental control, making such systems both technologically advanced and cost-effective.

Previous research has explored various aspects of microclimate regulation for agricultural applications. Managing microclimate factors such as temperature, humidity, and light intensity is essential for optimal plant growth. One study examined the effects of UV LED intensity on the growth of red lettuce in hydroponic systems, illustrating how precise control of light conditions can lead to improved crop yields [4]. This finding is further supported by a comprehensive review that analyzed the optimal temperature, humidity, and vapor pressure deficit for greenhouse cultivation, emphasizing the complex relationships between these factors and plant health [5]. Additionally, researchers have developed an automatic control system utilizing fuzzy logic to regulate the parameters of nutrient solutions in hydroponic systems [6]. The integration of IoT technology in smart greenhouse management has also been demonstrated, where microcontrollers are employed to automate the control of temperature and humidity, ultimately enhancing the efficiency of agricultural practices [7]. While these studies underscore the potential of IoT and control systems in agriculture, their applications in TSS seedling cultivation remain largely unexplored. Moreover, there is a significant gap in research regarding the design of monitoring and control systems specifically for shallot TSS cultivation in controlled environments.

This study seeks to bridge this gap by designing and implementing a climatic chamber with an IoT-based monitoring and control system, especially for the TSS seedlings stage. The system uses microcontrollers, sensors, and actuators that regulate temperature, humidity, light intensity, and nutrient solution parameters, ensuring optimal microclimate conditions. The system leverages the Blynk IoT platform for real-time monitoring and control, providing an intuitive user interface for farmers. Integrating Net Time Protocol (NTP) with Arduino IDE enables precise timing for actuator operations, ensuring synchronized control across various parameters. This research presents the design, implementation, and evaluation of the climatic chamber of the TSS seedlings process using IoT. Key objectives include developing monitoring systems for microclimate parameters, creating control algorithms for actuators, and evaluating system performance in maintaining optimal conditions for TSS. The study also explores the scalability and adaptability of broader agricultural applications, emphasizing its potential to transform smallholder farming practices. This research can also contribute to global efforts toward sustainable and efficient agriculture for shallot production.

2 Materials and methods

The research was conducted for data collection and analysis at the Bioinformatics Engineering Laboratory and Siswadhi Soeparjdo Field Laboratory Station, Department of Mechanical and Biosystem Engineering, IPB University Bogor, Indonesia. The methodology involves developing and testing a TSS seedling in a climatic chamber with an IoT-based control and monitoring system.

2.1 Materials and equipment

The study utilized a climatic chamber with a dimension of 155.3 × 194.5 × 102 cm, a thickness of 5 cm, and high-density polystyrene insulation. It was equipped with six trays for TSS seedlings with a total of 4,800 plant populations. The chamber's components include an air conditioner for temperature regulation, 24 LED growth lights for plant photosynthesis, ultrasonic atomizers for nutrient misting, and water pumps for nutrient distribution. Figure 1 provides a schematic representation of the climatic chamber design. Several electronic components were used to implement the monitoring and control system.

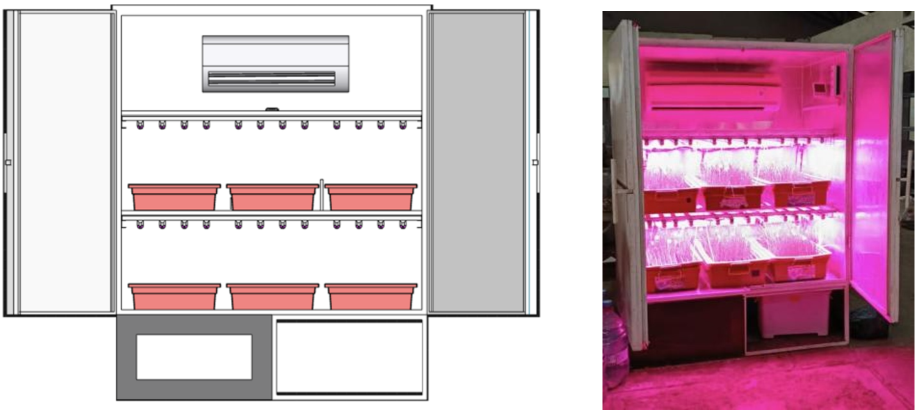


Fig. 1. Climatic chamber equipment for TSS seedlings

2.2 System monitoring and control design

The system was designed to monitor and control environmental parameters for TSS seedlings, including air temperature, humidity, light intensity, and nutrient solution temperature. The system architecture integrates sensors, a microcontroller, and actuators, with data transmitted to the platform for visualization and control. Table 1 shows the detailed components of the sensor and controller. The system operates on control logic implemented via the Arduino IDE. Actuators are triggered using a relay module based on the threshold value and timing intervals. Environmental data from sensors is processed in real time and displayed on the Blynk application dashboard.

Table 1. The components used in the monitoring and control system

No	Component	Description
1	Node MCU Lolin Lua Wi-Fi V3 ESP8266	Microcontroller for executing commands and enabling Wi-Fi connectivity.
2	Base plate board Node MCU Lolin Lua Wi-Fi ESP8266	Base for Node MCU Lolin V3, expansion I/O, expansion power VCC/GND
3	DHT21 AM2301 Sensor	Measures temperature and humidity.
4	GY-302 BH1750 Sensor	Measures light intensity and radiation.
5	DS18B20 Waterproof Sensor	Measures the nutrient solution temperature.
6	Relay Module (4 channels)	Controls the on/off operation of various actuators (lights, pumps, atomizers, air conditioner).
7	Air Conditioner	Actuator for temperature and humidity parameter
8	LED Growth Light	Actuator for light intensity and PPFD control
9	Pump Diaphragm	Actuator for debit nutrition control
10	Ultrasonic Atomizer	Actuator for aeroponic water irrigation control
10	Arduino IDE	Software for coding and programming the microcontroller.
11	Blynk IoT Platform	Provides user interface for real-time monitoring and control via cloud.

Electronic components are placed in a control box at the back of the chamber. A closed-loop control system is used to design the control system. Software design involves program codes for electronic instruments on the Arduino IDE dashboard so that each component connected to the microcontroller can run the program according to the specified commands. The Blynk IoT application is used for the system monitoring stage, which can display a user interface related to the results of reading the sensors used in the chamber during the TSS seeding process. The 4-channel relay connected to the ESP8266 will work with the on/off command according to the specified target value. The design concept has several functions to achieve the system design objectives. Figure 2 shows a schematic representation of the system design.

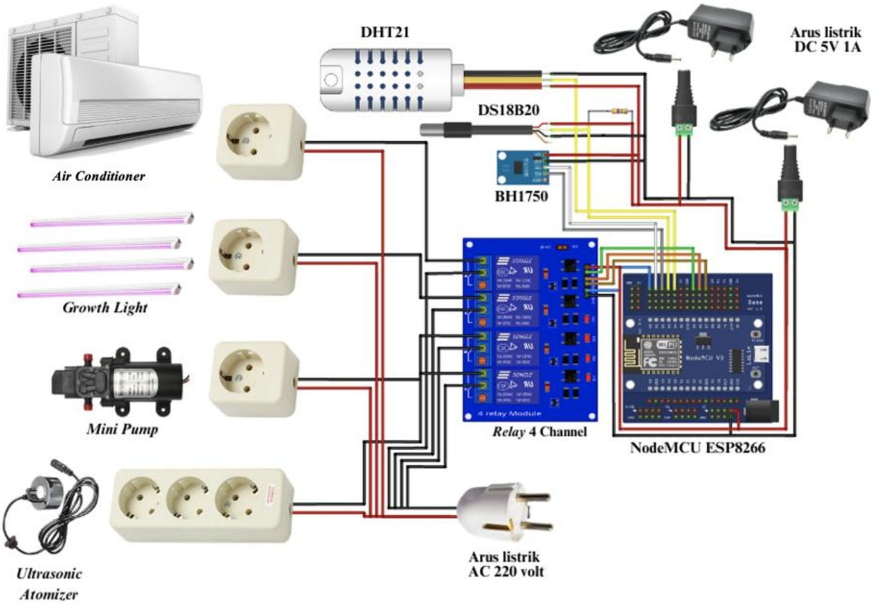


Fig. 2. The schematic diagram of the control and monitoring of the system

Various sensors are connected to the Node MCU ESP8266 microcontroller. The measurements from the sensors were sent to the server and displayed on the Blynk IoT display as a monitoring dashboard. The control system uses the Arduino IDE, incorporating the millis syntax and the Network Time Protocol (NTP) module to enable precise parameter control based on scheduled activation and deactivation durations. The millis function measures elapsed time in milliseconds since the microcontroller was powered on, allowing time-based operations without halting program execution. This non-blocking approach ensures that multiple tasks run concurrently while maintaining accurate control over timing intervals.

In addition to software-based time tracking, the NTP module synchronizes with online time servers to retrieve real-world time with high accuracy. By leveraging this synchronization, the control system can operate according to an absolute time reference rather than relying solely on internal counters. This integration is particularly advantageous in applications requiring precise and consistent scheduling, as it eliminates errors associated with clock drift in traditional real-time clock (RTC) modules.

By combining these two techniques, the control system effectively regulates the activation and deactivation of connected devices according to predefined schedules. The millis function ensures seamless operation within the microcontroller, while the NTP module guarantees accurate timekeeping. This approach is applicable in various automation systems where scheduled operations must be executed reliably and efficiently [8,9,10].

2.3 Experimental setup

To ensure accuracy, all sensors were calibrated before deployment. The DHT21 and DS18B20 sensors were calibrated with a standard temperature and humidity data logger (Elitech GS20), achieving high reliability with coefficients of determination. Electronic components were assembled in a protective control box to prevent damage from external factors such as water. Sensors were strategically placed within the chamber to optimize readings. The DHT21 sensor was positioned at the top center for ambient air measurement. The DS18B20 sensor was placed in the nutrient solution trays to monitor the temperature. The BH1750 light sensor was located near the plant trays to capture light intensity. Relays and power supplies were also housed in the control box, with connections established to actuators for environmental adjustments. The sensors position layout can be seen in Figure 3.

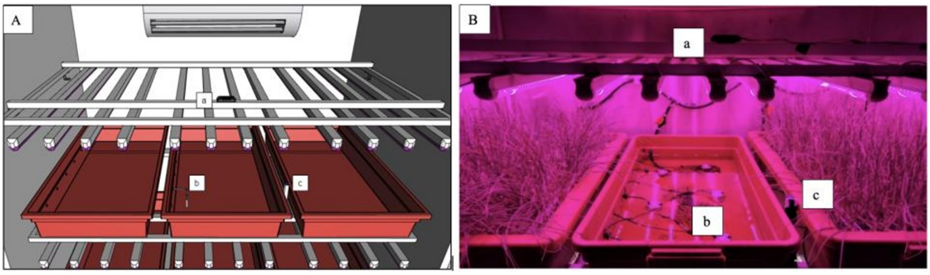


Fig. 3. The sensor position of (a) DHT21, (b) DS18B20, dan (c) BH1750 for monitoring and control system in the chamber

Control parameters such as mini pump diaphragm, ultrasonic atomizer, and growth light will be controlled using input in the target time value; for example, the LED light will turn on from 06.00 to 20.00, the pump will turn on for 5 seconds per hour, and the ultrasonic atomizer turns on for 15 minutes for second. When the target set point is reached, the ESP8266 will send low logic to the relay, activating the actuator. At the same time, the ESP8266 will send a binary logic value of 1 to the server, while when the relay is off, the binary logic value is 0. Table 2 shows the target point parameter for the controlled system in the TSS seeding stages.

Table 2. The set point target for a controlled environment in the chamber

Environmental parameter	Set point value	Actuator
Temperature	22 ± 3 °C	Air conditioner
Humidity	80 ± 5 %	Air conditioner/ Humidifier
LED Light Periodize	16 hour	LED growth light
Debit of AB Mix nutrition	5 second per hour	Pump diaphragm
Dose of Aeroponic Irrigation	15 minutes per hour, periodically	Ultrasonic atomizer

The system continuously monitored environmental parameters, with data logged every minute and transmitted to the Blynk platform. Graphs of parameter trends were generated to visualize stability and identify potential anomalies. Actuators were managed using real-time data inputs. For example, the air conditioner system was triggered to maintain temperatures between set points. All data were analyzed to quantify deviations from desired conditions. Standard deviations were used to assess accuracy and reliability. The calibration data were modeled using linear regression to evaluate sensor precision.

3 Result and discussion

3.1 Sensor calibration and system functionality

Calibration is critical to ensure accurate parameter measurement. Sensor calibration was conducted to provide precise environmental monitoring in the chamber for TSS seeding. Sensor accuracy directly influences system reliability, as deviations in data collection can lead to improper environmental control. Three primary sensors were calibrated: the DHT21 (temperature and humidity sensor) and BH1750 (light intensity sensor). Calibration was performed by comparing each sensor’s readings with standard reference devices, following methods established in previous agricultural IoT studies.

The DHT21 sensor for measuring temperature and humidity was calibrated using the Elitech GSP-6 data logger, which has a high precision rating for environmental monitoring applications. The temperature calibration produced a high coefficient of determination of $R^2 = 0.9786$, confirming good linearity and accuracy, while humidity calibration yielded $R^2 = 0.9396$, indicating reliable performance for maintaining stable microclimate conditions. Figure 4 presents the calibration curve for temperature and humidity, showing the close alignment of sensor readings with standard values.

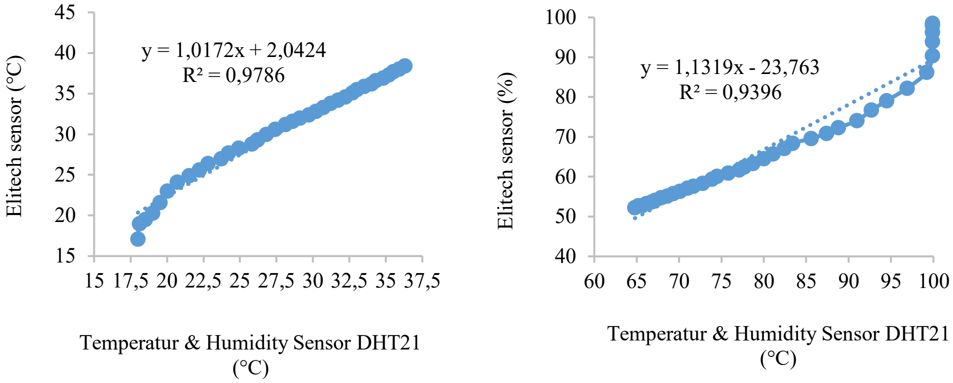


Fig. 4. Calibration curve of DHT21 sensor for temperature and humidity

Similarly, the BH1750 light intensity sensor was calibrated against the Photosynthesis Light Quantum Meter TES 1339P, a device for measuring photosynthetically active radiation (PAR). The correlation coefficient was $R^2 = 0.8664$, indicating good accuracy, though minor deviations were observed at high-intensity levels, likely due to sensor sensitivity limits. This aligns with findings from [11], which indicated that lux-based sensors may have limitations in accurately estimating PAR. Figure 5 illustrates the BH1750 sensor calibration.

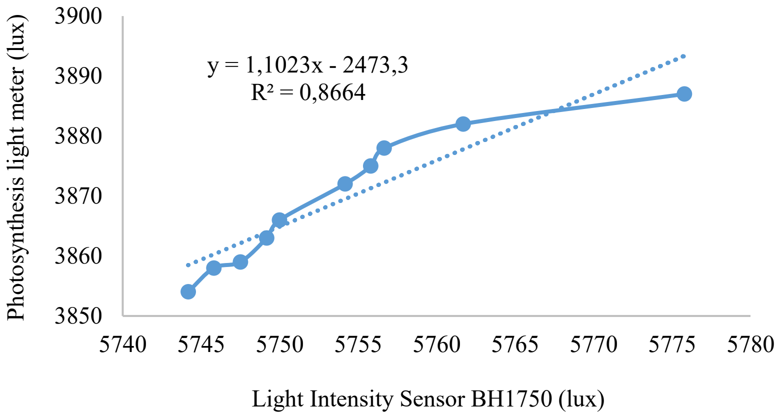
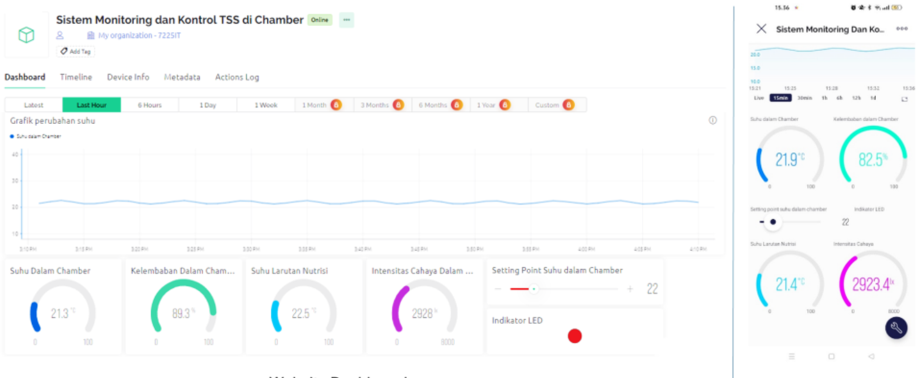


Fig. 5. Calibration of light intensity sensor

In addition to sensor calibration, system functionality was tested to ensure efficient data acquisition and processing. The ESP8266 microcontroller successfully received, processed, and transmitted data to the IoT-based Blynk platform, confirming its capability to handle real-time monitoring. The system's hardware components, including relay modules, were integrated within a protective control box to minimize external interference, such as moisture exposure and electrical faults. The design of the system allows for scalability and troubleshooting, ensuring adaptability for future expansions.

3.2 IoT-based system implementation and performance

The monitoring and control mechanisms were evaluated based on their ability to maintain stable microclimate conditions in the chamber, focusing on temperature, humidity, and light intensity. The IoT-based Blynk monitoring system provided continuous real-time updates accessible via web and mobile dashboards [12,13]. The study of [14] highlights how the Blynk platform facilitates continuous real-time updates that are accessible via web and mobile dashboards, enabling farmers to monitor soil moisture, temperature, and other critical environmental parameters. The findings suggest that such systems enhance agricultural productivity and contribute to environmental conservation by optimizing resource usage. Transmission delays between the ESP8266 microcontroller and the cloud platform were measured at 3–8 seconds, which is acceptable for agricultural automation. Figure 6 shows the Blynk dashboard interface displaying real-time environmental parameters.



Website Dashboard

Mobile Apps Dashboard

Fig. 6. Blynk IoT dashboard interface

The temperature control system regulated chamber conditions within 20.25–22.79°C, with a standard deviation of ± 0.64°C, ensuring minimal fluctuations. This range aligns with previous research indicating that TSS seedlings require temperatures between 18–22°C for optimal physiological development [15]. Figure 7 illustrates the temperature trends over a 16-hour monitoring period, demonstrating the system's stability. The fluctuation in temperature changes is faster when the plant lights are on, whereas when the plant lights in the chamber are off.

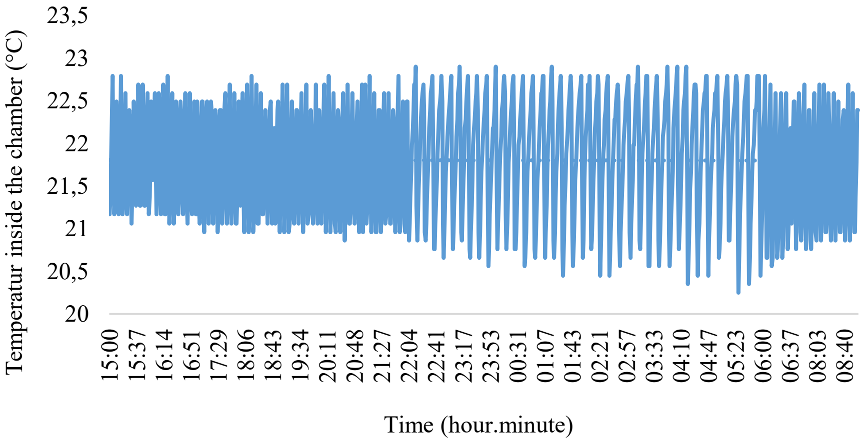


Fig. 7. Temperature trends inside the chamber.

Several factors influence changes in environmental humidity within the chamber. These include the operation of the lights, the presence of nutrient solution mist released from the plant tray, and the opening and closing of the chamber door, which allows outside air to enter. Humidity levels were maintained at 77.66–89.31% (SD: ±2.11%) and achieved through ultrasonic atomizers operating at pre-programmed intervals. Figure 8 presents humidity variations over time. The relative humidity above 75% enhances aeroponic growth efficiency, preventing excessive water loss from transpiration while maintaining optimal root hydration. Nutrient solution temperature was kept within 20–25°C (SD: ±1.06°C), ensuring a stable root-zone environment. Temperature fluctuations in the nutrient reservoir were primarily caused by ambient heat exchange and atomizer operation.

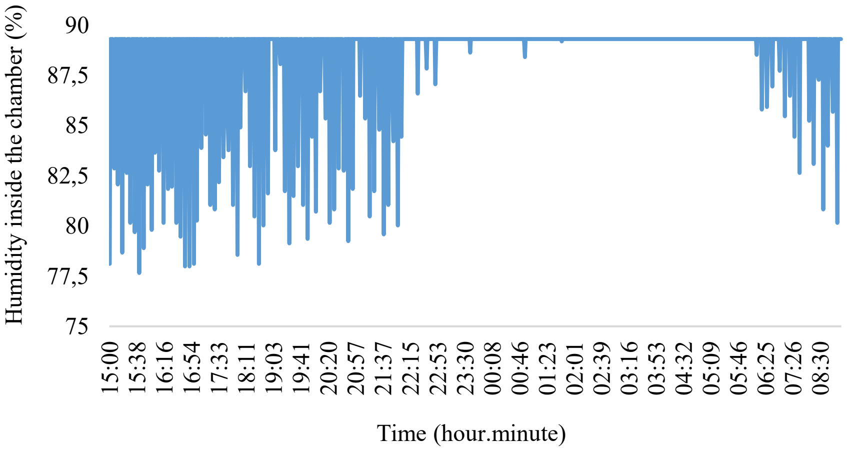


Fig. 8. Humidity fluctuation inside the chamber.

During photoperiods, light intensity inside the chamber remained between 2800–2900 lux (SD: ±10.55 lux). The light intensity value of zero indicates that the LED is off because it was used in the chamber for 16 hours, starting at 06:00–22:00 during the seeding process. However, sensor readings showed slight reductions as seedlings grew taller, partially obstructing measurement zones. Figure 9 shows the light intensity distribution. Studies from [11] recommend monitoring PAR values instead of lux to enhance accuracy in photosynthetic efficiency assessments. Future system iterations should integrate PAR sensors to improve precision.

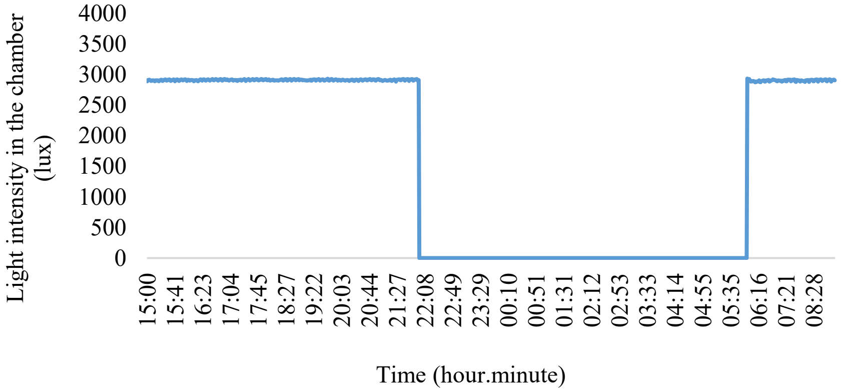


Fig. 9. Light intensity variation inside the chamber

The atomizer control system for misting the nutrient solution onto plant roots during TSS seeding in the chamber operates on a specific schedule. The atomizer is activated for 15 minutes and then deactivated for 45 minutes, repeating this cycle every hour. As depicted in the atomizer control graph (Figure 10), a binary logic value of 1 indicates that the atomizer is on, while a value of 0 means that it is off. The program managing the atomizer uses the millis function syntax, allowing precise control.

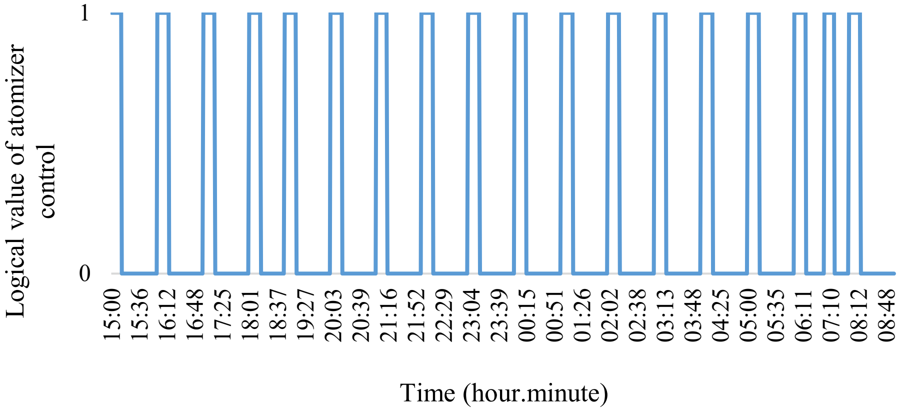


Fig. 10. Logical/binary value of atomizer control over the time

3.3 Performance of the system in response to temperature changes

The temperature control system was primarily managed through an air conditioning unit, activated via the ESP8266 microcontroller in response to temperature deviations beyond the predefined threshold of 22°C. The system was tested when external temperature variations influenced the chamber environment, requiring real-time adjustments. Figure 11 illustrates the temperature restoration over a monitoring period, showing the system’s capability to regulate disturbance conditions effectively.

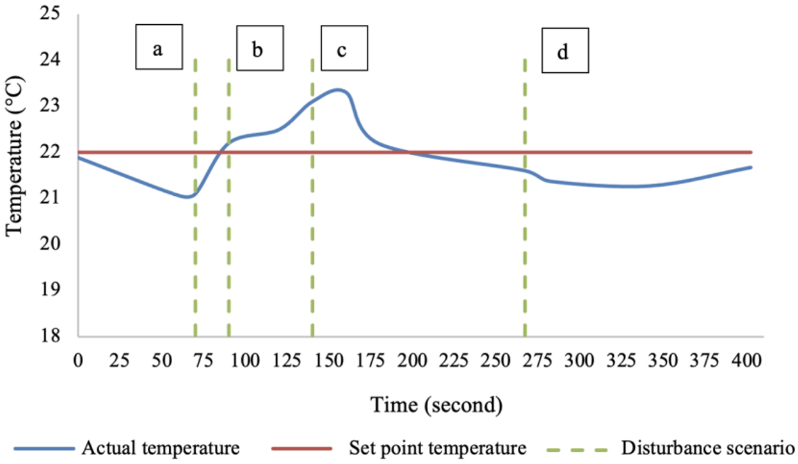


Fig. 11. Temperature restoration response after an external disturbance

The performance evaluation test of the compressor in relation to temperature changes was conducted with the chamber lights on and an initial ambient temperature of 21.1 °C. During the test, the chamber door was opened for 20 seconds (a), causing the temperature to rise to 22.2 °C. After the door was closed again (b), the compressor was turned on after a 30-second pause (c). At this point, the temperature had increased further to 23.1 °C. The chamber temperature dropped to 21.6 °C after the compressor ran for 2 minutes and 7 seconds (d). The test results indicated that when the temperature in the chamber increased due to the door opening, the compressor took a significant amount of time to cool the chamber back down to the lower temperature limit.

The success of the system design is evident from its performance during testing, where it effectively monitored and controlled the environmental conditions in the chamber throughout the TSS seeding process. The results indicate that the system operates as intended, responding accurately to specific commands and efficiently managing several parameters for both monitoring and control.

4 Conclusion

This study successfully developed and implemented an IoT-based environmental monitoring and control system for a climatic chamber to optimize True Shallot Seed (TSS) seeding. The system effectively regulated environmental parameters, including temperature (20.25–22.79°C, SD: ±0.64°C), humidity (77.66–89.31%, SD: ±2.11%), and LED light intensity (2800–2900 lux, SD: ± 10.55 lux). These conditions were highly precise, ensuring an optimal microclimate for seedling growth. The IoT-based monitoring system provided real-time environmental data. The system's automated control mechanisms, including air conditioning, atomizers, LED growth lights, and nutrient pumps, effectively maintained stable environmental conditions, making it a viable solution for controlled-environment agriculture (CEA). Future improvements should explore alternative communication protocols, utilization of PAR sensors for LED control, and renewable energy integration to enhance sustainability.

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