

IoT-based design for plant cultivation experiments and data logging

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ORIGINAL RESEARCH PAPER

Received: April 17, 2025 • Accepted: June 19, 2025

Published online: July 15, 2025

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ABSTRACT

Recent advancements in low-cost microcontroller platforms and Internet of Things (IoT) sensors have enabled the development of automated, modular growth chambers for precise environmental control in plant studies. This study presents a cost-effective, scalable chamber equipped with Wi-Fi-enabled sensors for real-time monitoring of temperature, humidity, CO₂, light intensity, and soil parameters. The system integrates an automated irrigation mechanism, programmable lighting, and cloud-based data management system. The design ensures independent sensor operation, preventing system-wide failures while maintaining experimental reproducibility. The results demonstrate that this approach significantly reduces costs while maintaining a reliable working system, providing high-resolution environmental control and making it suitable for diverse agricultural and botanical research applications.

KEYWORDS

IoT, indoor farming, smart agriculture, controlled environment, precision agriculture

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1. INTRODUCTION

Smart farming, also known as precision agriculture, is the application of modern Information and Communication Technologies (ICT), such as the Internet of Things (IoT), artificial intelligence (AI), big data, drones, robotics, and cloud computing to enhance agricultural productivity, optimize resource usage, and improve sustainability (Wolfert et al., 2017). Smart farming leverages real-time data collection, automation, and analytics to make precise, data-driven decisions (Kamilaris et al., 2017).

The technological evolution of Agriculture 5.0 employs cutting-edge technology for plant cultivation; beyond automation and digitization incorporated into production systems, Agriculture 5.0 is a profound integration between humans and machines (Fountas et al., 2024). The use of AI stands out, where not only data are applied but systems that are able to learn and make decisions to adapt in real-time. Its main goal is to optimize and increase efficiency while reducing the environmental impact in order to build climate-adapted agricultural systems that are sustainable for this and future generations.

As sensor and IoT technologies advance, their costs rapidly decline, making smart farming solutions increasingly accessible. According to industry reports (Alsen et al., 2017), the price of basic agricultural sensors has dropped by over 60% in the past decade, with some soil moisture sensors now available for under \$20 (Amazon.com, n.d.). This cost reduction stems from mass production, improved manufacturing techniques, and the development of low-power, miniaturized components. Additionally, the emergence of open-source hardware platforms and affordable wireless communication protocols (LoRaWAN and NB-IoT) have significantly lowered the implementation barriers. Moore's Law progress in semiconductor technology has enabled more powerful sensors at lower price points, while cloud computing's pay-as-you-go models eliminate the need for expensive local infrastructure (Roser et al., 2023). These trends democratize precision agriculture, allowing even small-scale farmers to benefit from technologies that were once exclusive to large agribusinesses (*Internet of Things: Low Cost Sensors for Agriculture*, n.d.).

Traditional farming methods often lack precision and efficiency, particularly in controlled cultivation experiments where environmental factors such as temperature, humidity, soil moisture, and light intensity must be meticulously regulated. Smart agricultural systems address these challenges by deploying sensor networks that collect and transmit critical data to cloud platforms for storage, analysis, and remote access. The Internet of Things allows the connection of daily tools to the web of computers, making data transfers to the cloud in real-time or in a short span like every minute (Ray, 2017). The integration of IoT and cloud computing has revolutionized modern agriculture by enabling real-time monitoring and data-driven decision-making in cultivation practices.

This approach improves crop yield and resource efficiency and reduces human intervention, making it ideal for research-oriented cultivation studies (Vangala et al., 2020). Furthermore, cloud integration allows researchers to access historical and real-time data from anywhere, facilitating collaborative experimentation and data sharing (Patil and Kale, 2016).

This article presents an IoT-cloud system constructed with a limited budget for cultivation experiments. Detailing its architecture, sensor network, cloud-based data processing, and collected results. By leveraging IoT and cloud technologies, this system aims to optimize experimental accuracy, reduce manual labor, and provide scalable and cost-effective solutions for

precision agriculture. The system's automated data logging, predictive analytics, and remote control of agricultural parameters enhance crop yield and resource efficiency, making it ideal for research-oriented cultivation studies and allows researchers to access historical and real-time data from anywhere.

2. PLANT GROWTH CHAMBER

The automatic standardization of environmental variables transforms cultivation experiments, ensuring efficiency, quality, and predictability, which is valuable for agronomic research, commercial plant production, and precision agriculture.

When environmental variables, such as temperature, relative air humidity, light, ventilation, and CO₂ concentration, are controlled and standardized by an automatic system to conduct a biological or agricultural experiment, it can achieve more precision, traceability, and reproducibility. More rigorous control of external variables allows more consistent and replicable results. The application of ICT extends to sensible cultivation and growth of plants with high economic value (Khan et al., 2024). Plants and microorganisms present ideal productivity when kept at ideal environmental conditions. Cultivation experiments present better germination rates, photosynthesis, fewer diseases, and stress reduction when ventilation, humidity, and hydration are provided (Reed et al., 2022). Additionally, while avoiding water stress and providing ideal light and temperature, cultivation can be held throughout the year, disregarding the outside conditions, especially for cold regions.

Sensors applied in ICT for agriculture allow a registry of information and, therefore, on-time adjustment to the cultivation status. For instance, soil sensors that measure nutrient content will allow fertilization to replenish the necessary nutrients before plants present deficiency symptoms.

To address the challenge of conducting cultivation experiments, a growth chamber was designed to assist researchers in creating an optimal, controlled environment for seedling germination and development during transplant production. At MATE's Institute of Technology, an experimental chamber has been developed to test different plant substrates and fertilization to mimic extraterrestrial soil. This chamber can also be used for various other cultivation tests, such as disease-free planting, genetic propagation, and research. The project, funded by the European Space Agency (ESA) and conducted partly in collaboration with the agency, aimed to test indicator crops and their viability in cultivation experiments within the chamber.

In that system, standardizing environmental variables can decrease experimental error or residual variance. Controlling environmental variables is a crucial strategy for minimizing residual variance and enhancing experimental control, ensuring that observed effects are attributable to manipulated treatments rather than uncontrolled environmental noise.

Given the constraints of a limited budget and the objective of developing an easily reproducible chamber for cultivation experiments, the following requirements were established. The lamp needed to be a plant growth light capable of illuminating an area of approximately 1 m², with a spectral composition resembling sunlight, adjustable intensity, user-friendly operation, and compatibility with standard power supplies. Essential measurements included

environmental humidity and temperature, soil moisture and temperature, soil NPK content, pH, conductivity, and automated data logging to an SD card.

Based on these specifications, a simplified plant growth chamber was designed with full control over environmental variables, ensuring consistent and reproducible conditions. The system integrated various sensors to monitor key parameters such as temperature, humidity, light intensity, soil nutrition status, and CO₂ concentration. The system wirelessly transmits real-time data to a cloud-based monitoring interface.

To enable environmental monitoring and control in the plant growth chamber, the Arduino-compatible microcontroller featuring built-in Wi-Fi was programmed to collect data from connected sensors and transmit it to a cloud server. The process begins with initializing the hardware, where sensors measuring temperature, humidity, soil moisture, light intensity, or other parameters are connected via I²C, SPI, or analog pins. The microcontroller also interfaces with actuators, such as relays for lights or irrigation pumps, allowing automated control based on sensor inputs or cloud commands.

The firmware, written in the Arduino IDE (C++), follows a structured workflow. First, the Wi-Fi connection is established using the ESP8266WiFi library, enabling internet access. Once connected, the microcontroller reads sensor data at predefined intervals (every 10 s) using appropriate sensor libraries (DHT.h for temperature or analogRead() for soil moisture). The collected data is formatted into a JSON payload, which includes the sensor readings and the device's MAC address for identification. This payload is sent to a cloud server via an HTTPS POST request using the ESP8266HTTPClient library, ensuring encrypted and secure data transmission.

The cloud server, which was developed using the PHP-based Laravel framework, receives the data, logs it into a database, and may send back commands in the HTTP response. The control command contains the delay until the next connection and the LIGHT ON/OFF parameter. The lighting program was implemented in the cloud software, and when connected, the actuator only receives the command to switch on or off. This bidirectional communication ensures real-time monitoring and remote control of the growth chamber.

Error-handling mechanisms are implemented to enhance reliability. If Wi-Fi connectivity is lost, the system can store data locally on an SD card or enter a low-power deep sleep mode until the connection is restored. Security measures like API key authentication or TLS encryption are also integrated to prevent unauthorized access.

By combining cost-effective hardware (Arduino/Wemos), standardized communication protocols (HTTPS), and modular programming, this system achieves scalable and reproducible environmental control for plant studies. Future expansions include machine learning-based automation and integration with additional sensor networks for more complex experiments.

Wi-Fi-enabled sensors were employed to monitor environmental variables, including temperature, humidity (The commercially available DHT22 physical sensor exhibits a temperature repeatability of ± 0.2 °C, a resolution of 0.1 °C, and an accuracy of ± 2 °C at 25 °C. For relative humidity, it provides a repeatability of $\pm 1\%$ RH, a resolution of 0.1% RH, and an accuracy of $\pm 2\%$ RH at 25 °C), CO₂ concentration (The commercially available MH-Z19B infrared CO₂ sensor is designed to measure carbon dioxide concentrations in the range of 400–5,000 ppm. It offers an accuracy of $\pm(50 \text{ ppm} + 5\% \text{ of the reading})$, a resolution of 1 ppm, and a repeatability of $< \pm 20$ ppm), and light intensity (The DS5-5528-LDR photoresistor has a spectral response of 400–700 nm, a spectral matching accuracy (SMA) of $\pm 10\%$, a dark resistance

>1 M Ω , and a resistance of 10–20 k Ω at 10 lux.), while also regulating the illumination system. These sensors enable the simulation of natural diurnal cycles or customizable light programs with a temporal resolution of up to one minute, facilitating studies on photoperiodic responses or light stress. The system architecture is decentralized, such that the failure of an individual sensor does not compromise overall system functionality, unlike centralized configurations. Each Wemos microcontroller is preprogrammed with Wi-Fi credentials, enabling autonomous network connectivity. The use of Wi-Fi ensures high scalability and flexibility, while the wireless design enhances resistance to water-related damage. Sensors are integrated automatically; upon power-up, a device connects to the designated Wi-Fi access point and subsequently to the cloud application based on its embedded firmware. The cloud registers the device but begins data acquisition only after the sensor is assigned to a specific measurement task. This modular approach supports dynamic expansion of the measurement system. **Figure 1** shows the proposed communication model.

A dedicated data acquisition system was developed, consisting of custom software and a cloud-based platform built on a PHP MVC framework. The sensor nodes were constructed using Arduino-compatible Wemos D1-R3 microcontrollers, supplemented with custom-designed shields following the specified circuit architecture.

The measurement system operates through HTTPS GET requests, transmitting sensor MAC addresses and measured values to the cloud server. Each sensor initiates measurements at 10,000 ms intervals upon power-up, with the server processing both new and recognized devices. This architecture permits real-time data visualization during system configuration while

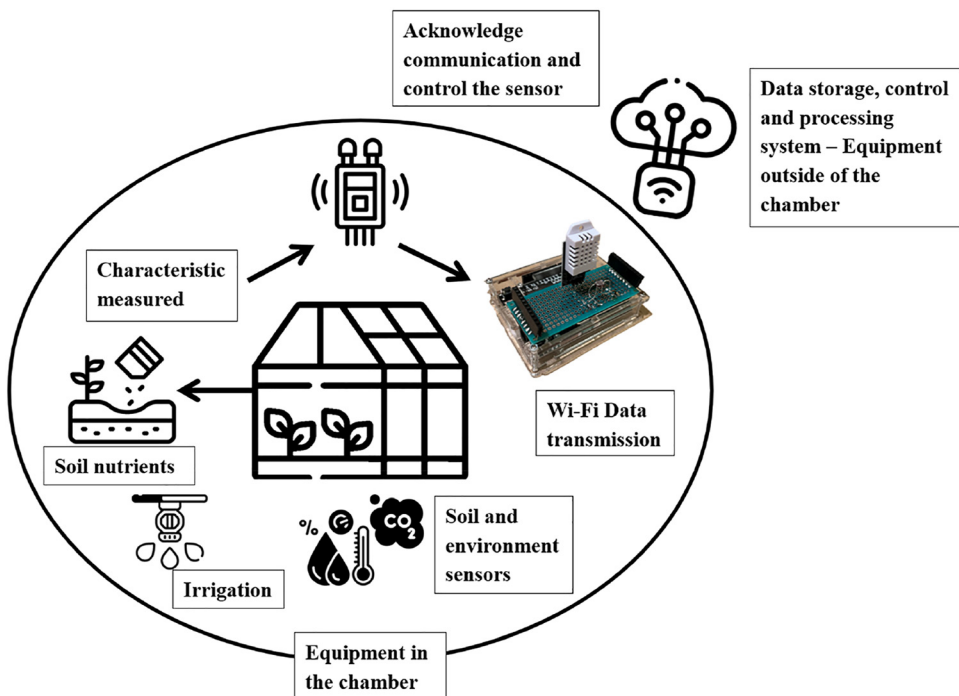


Fig. 1. Representative model of communication, exhibiting inside and outside actions

preventing redundant storage of initialization measurements. Command-response protocols are implemented through server replies, enabling remote control of sensor nodes.

Nowadays, a fully equipped chamber with sensors and controls, which were once costly and labor-intensive, can be achieved using inexpensive sensors and Arduino boards. The chamber was placed in a climate-controlled laboratory with constant temperature and humidity. The final constructed apparatus, represented in Fig. 2, demonstrates ongoing experiments, with the display visibly presenting real-time measurements from the soil sensors. A key advantage of this design is its modular expandability, which allows adaptation to different experimental requirements while retaining its core structure. This flexibility ensures compatibility with diverse soil and plant testing criteria.

2.1. IoT platform and sensors control

The lamp controller operates similarly to other Wi-Fi-enabled sensors in the system. Upon initialization, it establishes a connection with the cloud application to receive configuration parameters, including connection frequency and operational instructions for lamp control. The cloud platform dynamically assigns appropriate settings to each controller based on pre-defined lighting programs, to ensure synchronized system operation.

The light program is stored in the cloud, and the lamp controller only receives the on and off parameters when connected. The program structure, for example, is 10,p,0|10,s,1, which keeps the light off for 10 min and then turns it on for 10 s. The program can be expanded simply by adding a “|” (pipe) symbol and a new program element. For safety reasons, we use complete galvanic isolation with the relay panel so that we can power the LED panel with 220 V (Fig. 3).

The developed cloud software has four major functions, as shown in Fig. 4. The device management interface in “IoT sensors” displays all connected sensors by their unique MAC addresses. In “Measurements,” the experimental configuration is handled through a dedicated module that enables sensor assignment to specific protocols, including temporal parameters and lighting program selection. “IoT data” is a separate data repository that stores raw measurements with filtering and export capabilities for further analysis. The platform also includes visualization tools, “Charts” which generate graphical representations of the collected data for immediate assessment.



Fig. 2. Constructed chamber for different experimental setups

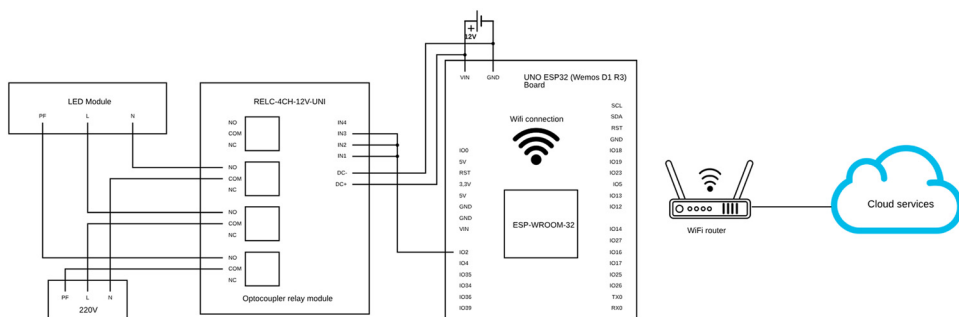


Fig. 3. Wiring diagram of the lamp control Wi-Fi actuator

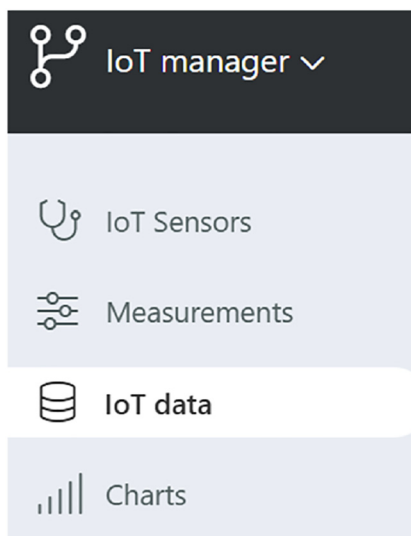


Fig. 4. Data management web page

The platform's programmability enables dynamic control of environmental parameters. The actuators responded to commands within <10 s, with lighting schedules adjustable via the cloud interface. The system design emphasizes flexibility in configuration while maintaining robust data management capabilities. Each component operates independently, but remains coordinated through the central cloud platform, ensuring reliable performance across all experimental conditions.

This implementation demonstrates how modern IoT solutions can effectively replace traditional environmental control systems. The system achieves precise environmental regulation by leveraging cost-effective hardware with cloud-based management while offering scalability for diverse experimental requirements. This approach significantly reduces both the complexity and cost typically associated with controlled environmental research.

2.2. Soil sensor and irrigation

The soil sensors used were multiparameter sensors, model RS485 output Soil NPKTHPH-S, capable of measuring temperature, humidity (soil moisture), electrical conductivity (EC), pH, and soil fertilization status for macronutrients (NPK) (Fig. 5).

It is a low-cost yet reliable device commonly used for agricultural and environmental monitoring applications. This low-cost soil sensor becomes a powerful tool for real-time monitoring and data collection when connected to an LED display and a data logger. The sensor continuously measures key soil parameters such as moisture, temperature, and conductivity, transmitting the data through its RS485 interface. The data logger records all sensor readings at set intervals, creating a historical dataset for analysis. To ensure the soil sensor accuracy, the sensors were calibrated using classical chemical analytical methods in the laboratory at MATE University. The ranges and accuracies of the sensors are as follows:

- Temperature range: -40°C – 80°C , $\pm 5^{\circ}\text{C}$.
- Humidity: 0–100%, with an accuracy of 2–3% for the ranges of 0–50 and 50–100%.
- Conductivity: 0–20,000 us/cm , $\pm 3\%$ (0–10,000 us/cm); $\pm 5\%$ (0–20,000 us/cm).
- pH measurement range: 3–9 pH, ± 0.3 .
- Nitrogen, Potassium, and Phosphorus content: 1–1,999 mg kg^{-1} (mg L^{-1}), $\pm 1 \text{ mg kg}^{-1}$ (mg L^{-1}).

This setup allowed real-time monitoring of soil parameters where the indicator plants were growing, with key variables displayed for immediate visual feedback. With an attached touchscreen data logger, data were continuously tracked, and changes in values were saved. As a result, timely adjustments, such as fertilization and irrigation, could be made to optimize plant growth based on accurate, up-to-date data.

A drip irrigation system was assembled for controlled water delivery, though it was not controlled with the Arduino-based monitoring system. For the results plotted in this study, the experiment did not require a variable irrigation rate, which made it simple to use the timer included in the irrigation pump. The system utilized a small submersible pump connected to flexible tubing and adjustable drip emitters, ensuring targeted water distribution to plant root zones. Instead of microcontroller automation, the pump was regulated by an analog electromechanical timer, allowing manual scheduling of irrigation intervals; for instance, 1-minute cycles every 12 h were used in experiments. In this case, the water volume was calibrated over the

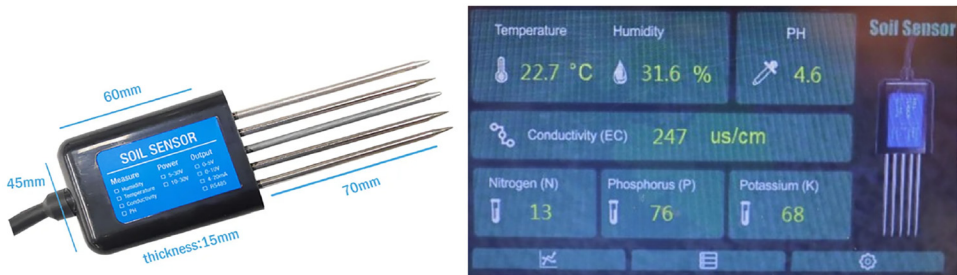


Fig. 5. Soil sensor and display

working time of the system to deliver the correct amount of water to the plants (Fig. 6). This simplified approach provided low-cost automation without requiring digital programming while maintaining consistent soil moisture levels for experimental reproducibility. In the current design, there was no need to implement adaptive irrigation. Still, the modular design of the system allows for the connection of a new Wemos microcontroller, which includes a soil moisture sensor on the shield and a relay actuator that operates a valve. When the soil moisture falls below a certain level, the microcontroller activates the actuator. This design provides a fast response to irrigation needs.

2.3. Collected data

The IoT monitoring system collected a total of 99,084 data entries between 18/01/2025 and 24/01/2025, with measurements recorded at 10-s intervals for illumination intensity, air temperature, relative humidity, and lamp status (binary on/off). This high-frequency sampling yielded a temporal resolution sufficient to capture dynamic environmental fluctuations within the growth chamber.

Key observations revealed that the relative humidity averaged 30% prior to 20/01/2025, necessitating system adjustments to achieve the target setpoint of 40%. This was accomplished through integrated humidification and airflow modulation, demonstrating the system's capacity for real-time environmental control. Illumination data is recorded in arbitrary units, with higher values corresponding to greater intensity, and temperature (°C) exhibited stable profiles, as illustrated in Fig. 7. The data plotted in this report exemplify the output from the treated data pool over 7 days, recorded every 10 s for illumination, humidity, temperature, and lamp, where the latter refers to on or off. The measured variables of one experimental setup are collected and portrayed in the graphs below, and the data were plotted by calculating the daily average.

The developed IoT platform was set up to allow visual analysis of the data, as shown in Fig. 8. The real-time visualization of raw datasets were computationally intensive, prompting the



Fig. 6. The water flow of the dripping emitters was measured and installed in the plant pots

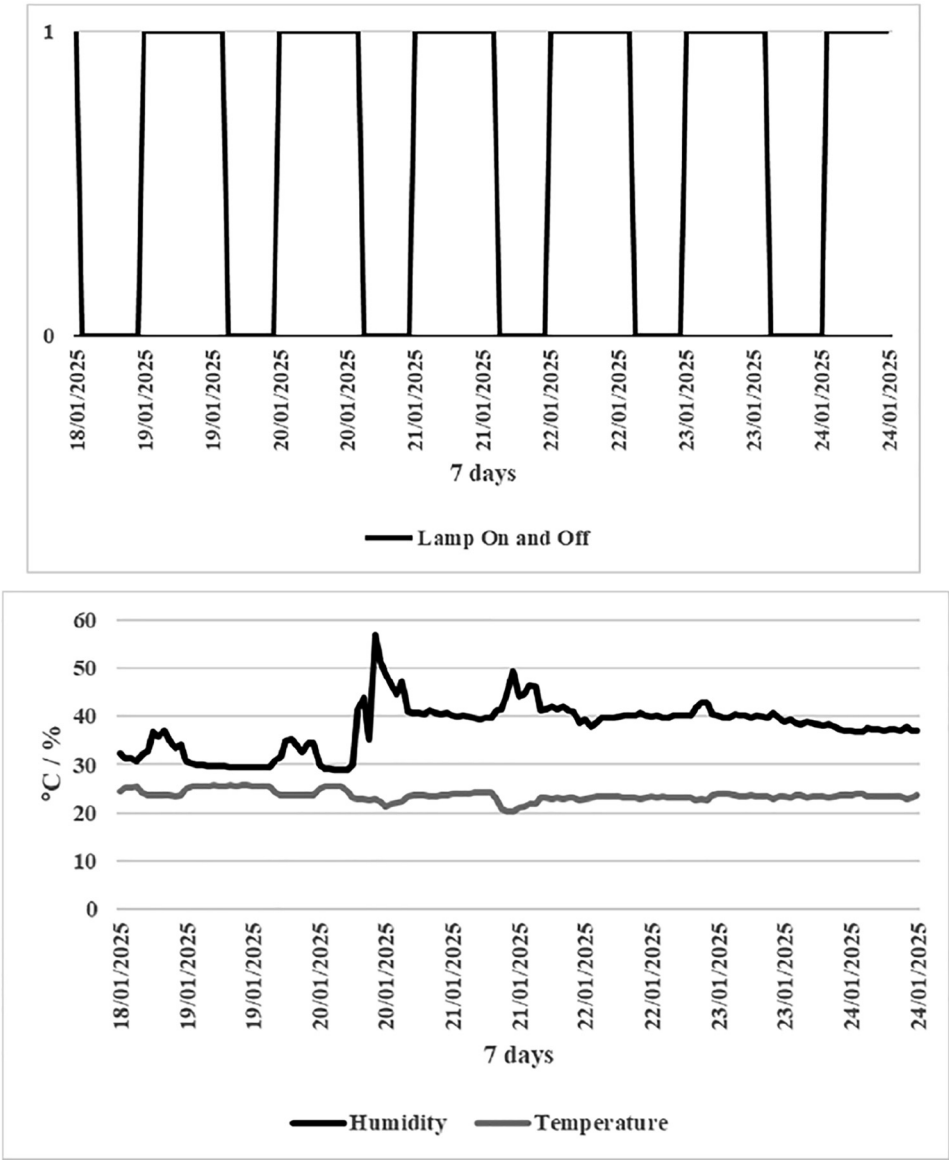


Fig. 7. Lamp 1 is on, 0 is off. Temperature (°C) and relative air humidity (%) measured over 7 days

implementation of a data partitioning protocol. By segmenting weekly datasets into discrete batches in the web platform’s measurement interface, the system achieved seamless graphical rendering without loss of temporal resolution.

Light is measured using a DS5-5528-LDR light sensor, also known as an LDR (Light Dependent Resistor). This component operates in a manner where its resistance is dependent on the

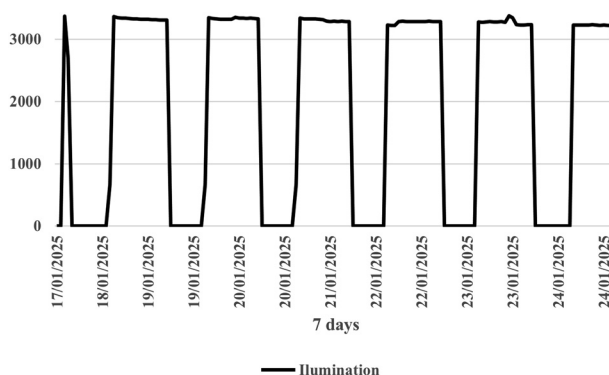


Fig. 8. Illumination program

intensity of the light falling on it. In darkness, the resistance of the LDR is high, while in light, its resistance decreases. Based on the variable resistance, we detect the light intensity as an analog voltage using a voltage divider. The voltage at the dividing point is measured on an analog input, and the result of the A/D conversion is shown in the diagram as a dimensionless metric. The curve serves two purposes. First, it confirms the execution of the lighting program and supports remote management by providing insight into the shape of the curve. Second, it helps determine an accurate DLI (Daily Light Integral) value for plant cultivation based on the characteristic curve. To determine the precise DLI, the numerical values are calibrated using the DLI-600 ePAR light and photoperiod meter.

The IoT monitoring system demonstrated robust performance in environmental data acquisition and control. The measurement accuracy was validated against reference instruments, with temperature readings maintaining a precision of $\pm 0.5^{\circ}\text{C}$, relative humidity within $\pm 3\%$. Data handling posed initial challenges due to the high sampling frequency (8,640 entries/day per variable).

The data collected for CO_2 are plotted in hourly average for 7 days in Fig. 9. Daily averages revealed stable CO_2 levels, fluctuating between 650 and 1,000 ppm, with an increase observed after 21/01/2025, likely reflecting photosynthetic activity by the plants. The highest concentration (1,000 ppm) occurred on 23/01/2025, followed by a steady decrease to 700 ppm by 24/01/2025, indicating adequate ventilation or plant-mediated drawdown. These data demonstrate the system's capability to resolve temporal variations in CO_2 , critical for studies on plant-environment interactions.

Soil parameters were systematically monitored over five weeks across multiple experimental setups, yielding a total of 26,350 sensor measurements. The weekly averages for key variables are summarized in Table 1, representing a soil type commonly used in space agriculture research. During the cultivation period, fertigation was employed to maintain nutrient levels, ensuring consistent replenishment for plant growth. The data revealed significant variability in soil characteristics, including nutrient content, electrical conductivity (EC), and pH. Nitrogen concentrations ranged from 11 to 20 mg kg^{-1} , while phosphorus (11–78 mg kg^{-1}) and potassium (3–71 mg kg^{-1}) exhibited broader fluctuations. Notably, Week 5 recorded the highest EC (241 $\mu\text{S cm}^{-1}$), suggesting a correlation between elevated soluble nutrient concentrations and

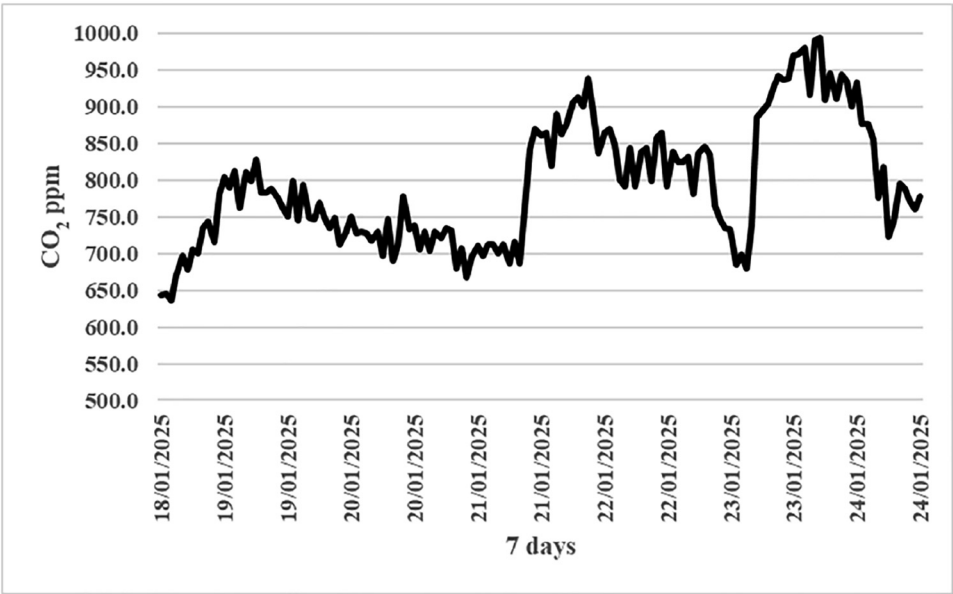


Fig. 9. CO₂ concentration

Table 1. EC, pH, and nutrient content average measured over 5 weeks

Week	Nutrients (mg kg ⁻¹)			EC (us/cm)	pH
	Nitrogen (N)	Phosphorus (P)	Potassium (K)		
1	14	11	3	113	8
2	20	23	15	137	6
3	16	78	71	125	5
4	11	19	11	130	6
5	11	73	65	241	6

increased conductivity. Soil pH varied from moderately acidic to alkaline (pH 5–8), with distinct trends in nutrient availability. For instance, Week 1 samples displayed the most alkaline conditions (pH 8) but the lowest nutrient and EC values, likely due to reduced nutrient solubility at higher pH. In contrast, Week 3 samples, with a more acidic pH (5), demonstrated higher nutrient levels and moderate EC, consistent with enhanced nutrient solubility in acidic environments.

The system’s real-time data visualization and manual fertigation protocols enabled precise control over soil conditions, ensuring that nutrient availability met the specific requirements of each trial. This approach proved effective for maintaining experimental consistency and addressing variability through targeted chemical corrections.

3. CONCLUSION

This study successfully demonstrates the feasibility of constructing a low-cost, automated plant growth chamber using off-the-shelf microcontroller platforms and IoT sensors. By integrating environmental monitoring with cloud-based control, the system achieves precise regulation of growth conditions while ensuring data integrity and remote accessibility. The modular architecture enhances scalability, allowing customization for different experimental needs without compromising core functionality. The system's performance was validated through high-frequency data collection and responsive actuator control. Notably, it enabled dynamic adjustments to environmental conditions. These insights underscore the system's utility in maintaining optimal growth conditions through manual or automated interventions.

Key advantages of this approach include its cost-effectiveness, modularity, and remote accessibility, which address common limitations of traditional growth chambers. The use of off-the-shelf components and customizable software makes the system adaptable to diverse research needs, from basic phenotyping studies to advanced investigations in precision agriculture. Future iterations could enhance functionality through machine learning-driven climate optimization or expanded multi-chamber networks.

Future enhancements of the system may include the integration of edge computing and onboard AI using Raspberry Pi devices, which offer sufficient computational power to run real-time machine learning models. This would enable the dynamic adjustment of environmental parameters, such as lighting, irrigation, or CO₂ levels, in response to sensor data and plant behavior. The addition of camera modules, combined with computer vision algorithms, would enable continuous visual monitoring of plant growth, health, and stress indicators. Such upgrades would significantly reduce the need for human intervention and transform the system into a fully autonomous, adaptive cultivation platform.

Declaration: The authors declare no competing interests.

Authors' contribution: Jessica Dias: Writing- original draft preparation, conceptualization, system development, data collection. András Revoly: Writing- reviewing and editing, conceptualization, system development, data collection. Zoltán Bártfai: Conceptualization. György Barkó: Conceptualization, writing- reviewing and editing.

ACKNOWLEDGMENTS

This study was possible thanks to the support of The European Space Agency ESA.

Thanks to the Stipendium Hungaricum Program for supporting Mechanical Engineering PhD research at the Institute of Technology of MATE University.

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

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