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Autonomous Smart μ Greenhouse: Analysis of Power Consumption Cum-sine IoT NodeMCUs ESP8266

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Abstract: This study presents the results of the first stage of the “COMMON Initiative: Climate-Smart Agriculture Demonstration Plot” project at the University of Central Asia – developing an autonomous smart micro-greenhouse with low-cost IoT equipment (two NodeMCU ESP8266 boards, four 3V relays, and sensors DS18B20/DHT11/LDR/YL-69) and analysing its power consumption in relation to the IoT component. The experiment with eight commonly cultivated plant species (dill, garden strawberry, lettuce, stock, basil, parsley, sorrel, and spinach) in two identical μ greenhouses of size 30x 26x 20cm each (testbed located at the elevation of 800m – Bishkek, Kyrgyz Republic) demonstrated that the power consumption is less with IoT equipment because the use of plant grow lights and heaters is minimised. Observational findings indicate that six plants (except basil and garden strawberry) grew faster in a smart μ greenhouse. The control algorithm employs one-input hysteresis with a neutral zone to automatically regulate the light and temperature inside a μ greenhouse. The percentage change for two time series (cum-sine IoT equipment) varies from -0.92% to -5.78% during the experiment. The data on temperature/soil moisture inside and the temperature/humidity/light intensity outside a μ greenhouse are provided to the human expert to support the decision-making process on plants' watering. In the second stage of this project, a machine learning algorithm will be employed to further minimise power consumption.

Keywords: micro greenhouse; IoT; power optimisation; automatic control; NodeMCU ESP8266.

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1. Introduction

The agricultural market shows a compound annual growth rate (CAGR) of up to 15% of the smart greenhouse share in selected countries of six major regions (Africa, Asia-Pacific, Europe, Latin America, the Middle East, and North America) from 2020 to 2025. The CAGR is predicted to be at the same level of up to 15% until 2034 (Data Insights Market, 2026; Mohd. Muzamil et al., 2025). Smart greenhouses are classified into several size-dependent categories: large (over 250 m²), medium (20-120 m²), small (4-10 m²), mini (1-3 m²), and micro (μ ; less than 1 m²) (Udrea et al., 2024; Ashok & Sujitha, 2021). Nowadays, μ greenhouses (μ GHs) are in a significant expansion because of the expanding population and the rise of urban farming with Internet of Things (IoT) affordable smart home tech (Udrea et al., 2024). To minimise the environmental footprint, near-zero energy consumption is the priority goal in the smart μ GH development (Soussi et al., 2025; Jawad et al., 2025). Analysis of existing IoT systems, such as those presented in Udrea et al. (2024) and Attia et al. (2025), indicates that datasets and actual power consumption depend on specific equipment, control algorithms, environmental conditions, soil characteristics, plant types, and many other parameters in μ GHs. This study presents the results of the first stage of the “COMMON Initiative: Climate-Smart Agriculture Demonstration Plot” project funded by the University of Central Asia – the design of an ad-hoc μ GH and analysis of its power consumption cum-sine low-cost IoT microcontrollers ESP8266 (Fathi, 2025).

The analysis of existing literature and online sources indicates that greenhouses employ heterogeneous IoT hardware (e.g., Raspberry Pi (Udrea et al., 2024), Arduino Uno (Attia et al., 2025), ESP8266 (Soussi et al., 2025), and ESP32 (Iyaomolereet al., 2025)), diverse control algorithms (e.g., artificial bee colony (Jawad et al., 2025), three-input hysteresis (Zubov et al., 2024), and fuzzy logic (Soussi et al., 2025)), and design (e.g., the shape of the roof (Šarić et al., 2025) and material of the frame shed (bamboo, steel, composite, etc.) (Guo et al., 2024)). The review of these publications indicates that no universal algorithm is currently available to accurately estimate the power consumption of IoT-enabled equipment under identical conditions (i.e., two similar micro-greenhouses with comparable IoT hardware and software operating simultaneously), and the impact of the internal environment on IoT sensors remains insufficiently explored.

This study presents a smart μ GH based on a low-cost IoT NodeMCU ESP8266 board and analysis its power consumption cum-sine IoT equipment. Also, the impact of the internal environment the μ GH on IoT sensors is discussed. The one-input hysteresis control algorithm is employed to separately control the light, watering, and temperature inside a μ GH. The ambient humidity at the testbed was approximately 40%, which is suitable for plant growth; therefore, humidity was not actively controlled within the micro-greenhouse, and natural ventilation was maintained during the experiment. This study shows that power consumption is less with IoT equipment than without it. Also, the capacitive moisture sensor is recommended for long-term utilisation since the resistive moisture sensor is prone to corrosion (Aziz et al., 2025).

The remaining part of the paper proceeds as follows: Section 2 reviews relevant studies on smart technologies for the design and control of micro-greenhouses and introduces the proposed smart μ GH architecture. Section 3 describes in detail the architecture of the smart μ GH prototype and the control of environmental parameters inside a smart μ GH. Section 4 presents the experimental testbed involving two micro-greenhouses equipped with low-cost IoT NodeMCU ESP8266 devices. Results and discussion are presented in Sections 5 and 6, respectively. Conclusions are summarised in Section 7.

2. Related works

The number of publications indexed in Web of Science related to μ GHs (the aggregated search with terms "micro greenhouse", "micro-greenhouse", and "microgreenhouse") has significantly increased between 2010 and 2025 (see Figure 1). Taking into consideration the analysis of power consumption, related papers discuss heterogeneous μ GH design, control

algorithms, monitored and controlled parameters and actuators, and configurations of hardware and software.

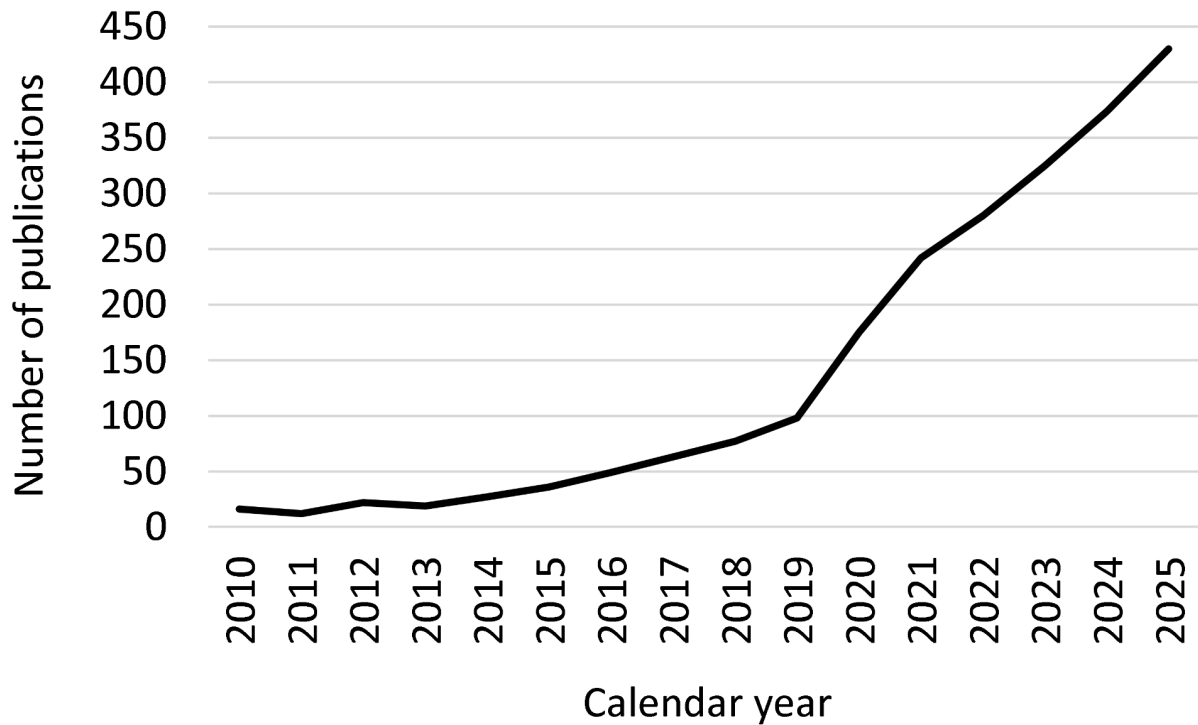


Figure 1. Web of Science papers related to μ GHs from 2010 to 2025

In the μ GH design, the shape of the roof is mostly taken into consideration, and the flat roof is the dominant form (Šarić et al., 2025). The semi-cylindrical shape increases spatial efficiency by up to 20% over standard rectangular greenhouses and improves environmental condition control precision, potentially enhancing crop development metrics by up to 30% (Attia et al., 2025). The μ GH can be made of different materials (Udrea et al., 2024; Guo et al., 2024), for example, using plexiglass mounted on aluminum profiles (Udrea et al., 2024). In this study, the commercially produced μ GH made of acrylic (see Figure 2) was selected among the multiple options.



Figure 2. Commercially produced μ GHs used in the study (with IoT smart equipment on the left and without it on the right)

Control algorithms can be classified into three main categories (Soussi et al., 2025) – classical (e.g., ON/OFF with hysteresis (Zubov et al., 2024) and proportional integral derivative (Attia et al., 2025)), advanced (e.g., model predictive, adaptive, and robust (Soussi et al., 2025)), and intelligent (e.g., fuzzy logic (Jawad et al., 2025), artificial neural networks (Venkataramanan et al., 2025; Al-Najadi et al., 2026), particle swarm optimisation, and genetic algorithm (Soussi et al., 2025)). In this study, a newly developed smart μ GH prototype was evaluated using eight commonly cultivated plant species: dill (*Anethum graveolens* L.), garden strawberry (*Fragaria $\times$ ananassa* Duch.), lettuce (*Lactuca sativa* L.), stock (*Matthiola incana* (L.) R.Br.), basil (*Ocimum basilicum* L.), parsley (*Petroselinum crispum* (Mill.) Fuss), sorrel (*Rumex acetosa* L.), and spinach (*Spinacia oleracea* L.). As the prototype was newly designed, no preliminary information for training, validation, and testing datasets was available, which precluded the use of more complex predictive control strategies. Consequently, a simple ON/OFF control algorithm with hysteresis was employed to regulate the temperature and light inside the smart μ GH. This approach ensured stable environmental conditions during the short 10-day experimental period, minimised unnecessary energy consumption, and provided sufficient data to evaluate the system's basic performance and feasibility.

A wide range of IoT sensors and actuators are employed in smart greenhouses. In Akpuluonu et al. (2024), an IoT-based greenhouse was constructed employing the following sensors and actuators: the air temperature and humidity (DHT11), resistive soil moisture (YL-69), and the detector of combustible gases and smoke (MQ-02); the cooling fan and heater for temperature control, water pump for automated irrigation, light bulbs for light conditions, and a fertiliser dispenser. In Pandurangi and Teradal (2025), optimal growing conditions for crops were implemented via the following sensors and actuators: DHT11, light-dependent resistor (LDR), resistive soil moisture sensor, and TCS3200 (a programmable color light-to-frequency sensor to convert light intensity into a frequency output - adaptive lighting and dynamic plant health monitoring); plant grow LEDs (light-emitting diodes). Attia et al. (2025), conducted an experiment at the University of Tebessa using the following sensors and actuators: DHT22 sensor for temperature and humidity monitoring, LDR BH1750, and HC-SR04 ultrasonic sensor to check tank water level; a 12V diaphragm water pump. Šarić et al. (2025), employed DHT11 and resistive soil moisture sensors ,along with a stepper motor (MS17HD2P417A-0) to control the opening and closing of the greenhouse cover. Iyaomolere et al. (2025), employed DHT22, YL-69, and PIR (passive infrared sensor detects human presence for security and system awareness) sensors to control the water pump, fan, and plant grow lights. In this study, sensors DHT11, LDR, YL-69, and the temperature module kit DS18B20 are employed to control the heater, plant grow lights, and watering inside the smart μ GH.

IoT microcontrollers, such as Arduino, ESP8266, ESP32, and ZigBee modules, as well as single-board computers such as Raspberry Pi, are used to acquire and process sensor data, after which actuators regulate environmental parameters within the micro-greenhouse. Since remote wireless control is the core requirement in the developed μ GH of an affordable price, the low-cost Wi-Fi IoT microcontroller NodeMCU ESP8266 is employed in this study.

The architecture of the proposed smart μ GH is shown in Figure 3: two ESP8266 microcontrollers use four 3V relays to manage actuators connecting / disconnecting power lines using data received from sensors. A0, D0, D2, D4, and D5 are designations of analog and digital pins on the ESP8266 board. The 1st NodeMCU ESP8266 controls the light inside the μ GH, switching ON/OFF two LED grow lights based on the data received from the LDR. Also, this microcontroller manages the temperature inside the μ GH (data from DS18B20), switching ON/OFF two portable 5V USB heaters installed under the μ GH. A human expert receives information on the ambient air temperature and humidity from DHT11, soil moisture from YL-69 (2nd NodeMCU ESP8266), light intensity from LDR, temperature inside the μ GH from DS18B20, and the state ON/OFF of four 3V relays via the HTML webpages hosted on web servers started on two ESP8266 microcontrollers. In this study, the additional hardware features are as follows:

1. The light and temperature inside the smart μ GH are controlled automatically with the possibility to change threshold values.
 2. The fan is not installed to control the humidity inside the smart μ GH since the ambient air humidity was in the range from 40% to 55% during the experiment, which is comfortable for plants' growing with natural ventilation inside the smart μ GH.
 3. The YL-69 soil moisture sensor was installed in the flowerpot with lettuce only. Hence, watering was manually implemented by a human expert because eight different plants with various water requirements participated in the experiment.
- Other equipment and algorithms are discussed throughout the paper.

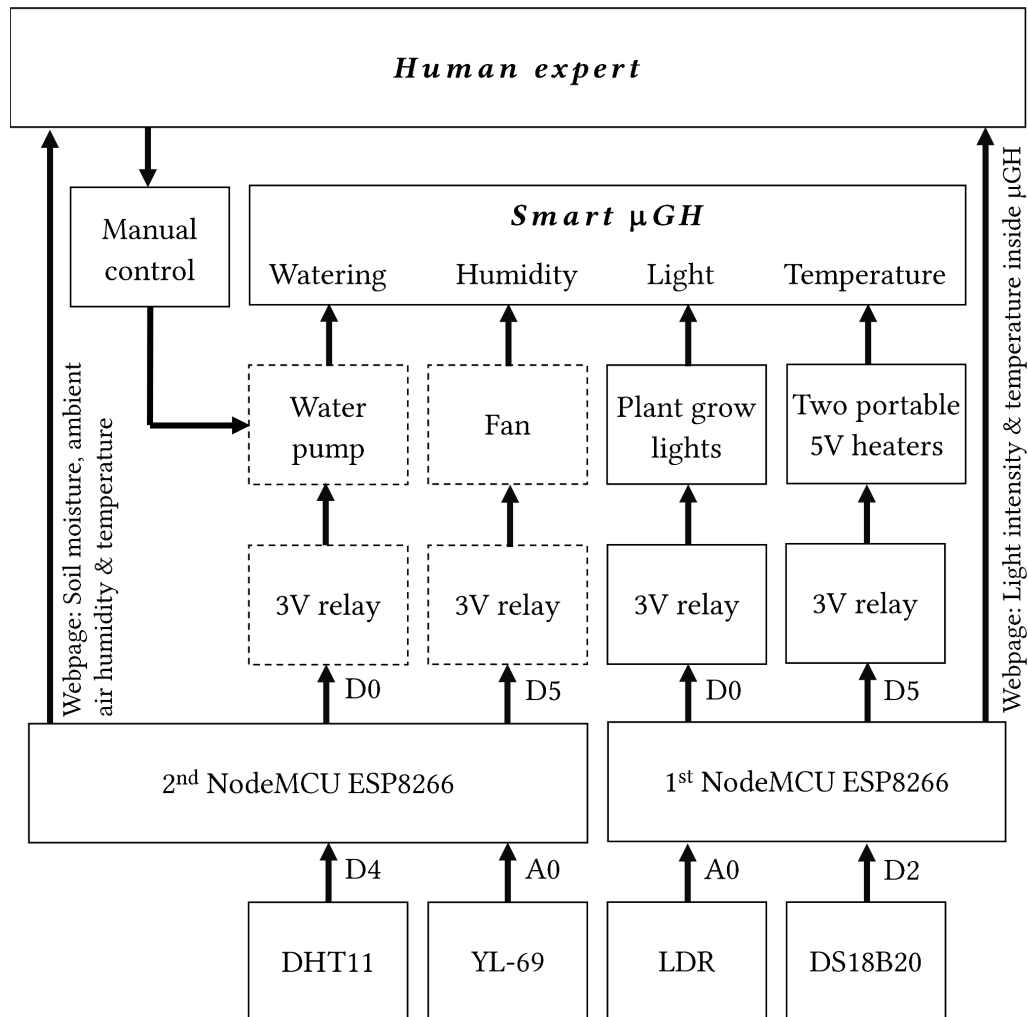


Figure 3. The architecture of the proposed smart μ GH

3. Methods

3.1. Architecture of smart μ GH prototype

The architecture of the proposed smart μ GH is presented in Figure 3. Two μ GHs are shown in Figure 2 – with (on the left) and without (on the right) the IoT equipment. Relays (JQC3F-03VDC-C in this study) are commonly used to connect/disconnect DC and AC power lines, regardless of the type of control technique (Tubburee & Ek-iam, 2025). States ON/OFF of four relays (see Figure 4) depend on the control algorithm, which is based on a one-input hysteresis system in the μ GH prototype:

1. Scenario 1. If the LDR value, (i.e., the light intensity), is greater than the value selected by the human expert (0, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 999 in this study) plus 25, then plant grow lights are ON. If the LDR value is less than the value selected by the human expert minus 25, then plant grow lights are OFF.
2. Scenario 2. If the temperature measured by the module kit DS18B20 inside a μ GH is less than the temperature selected by the human expert (15°C, 16°C, 17°C, 18°C, 19°C, 20°C, 21°C, 22°C, 23°C, 24°C, and 25°C in this study) minus 0.5°C, then two portable 5V USB heaters are ON. If the temperature inside a μ GH is greater than the selected by the human expert plus 0.5°C, then two portable 5V USB heaters are OFF.
3. Scenario 3. If the soil moisture measured by the YL-69 sensor inside a μ GH is less than the value selected by the human expert (29%, 31%, 33%, 35%, 37%, 39%, 41%, 43%, 45%, 47%, 49%, 51%, 53%, 55%, 57%, 59%, 61%, 63%, 65%, 67%, 69%, 71%, 73%, 75%, 77%, 79%, 81%, 83%, 85%, and 87% in this study) minus 1%, then it is recommended to water plants. If the soil moisture is greater than the value selected by the human expert plus 1%, then it is recommended not to water plants.

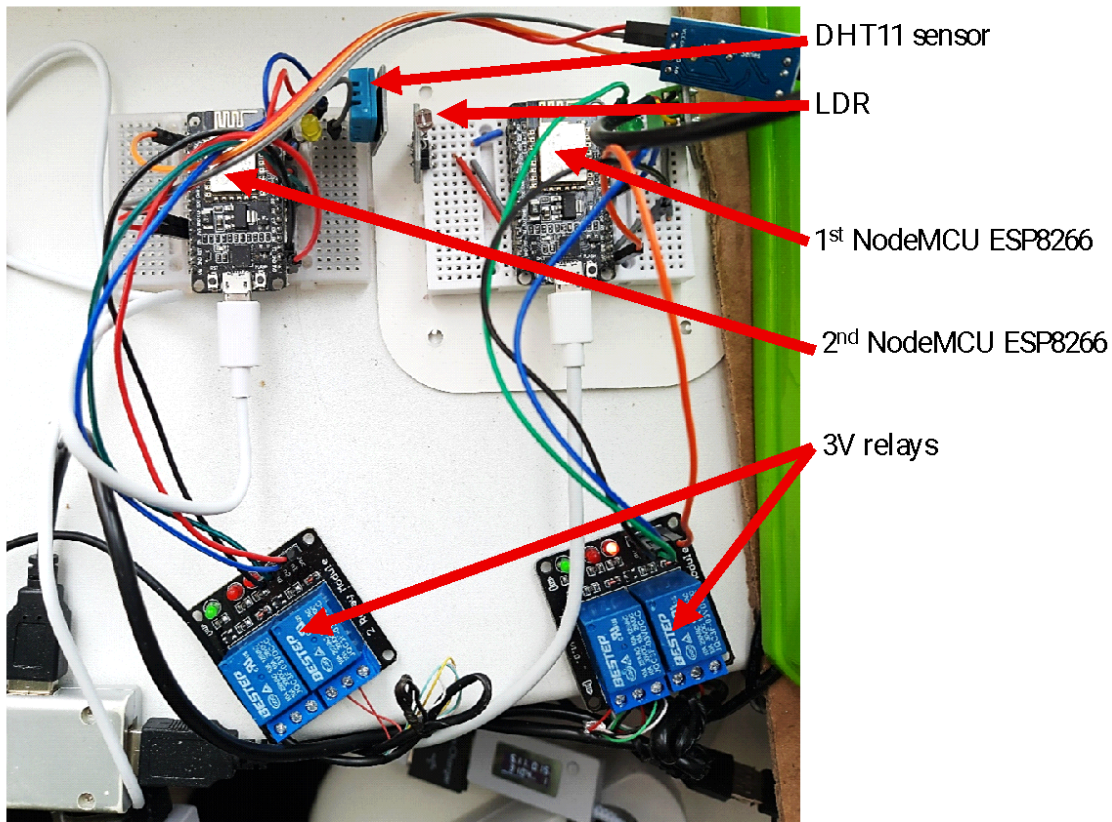


Figure 4. DHT11 sensor, LDR, four 3V relays, and two NodeMCU ESP8266 boards used for the automatic control of environmental parameters inside a smart μ GH

The installation of the DS18B20 temperature sensor, YL-69 soil moisture sensor, and two LED grow lights inside a smart μ GH is shown in Figure 5.

Two portable 5V USB heaters and a 5V diaphragm submersible water pump with water funnel, used in the project, are shown in Figure 6.

3.2. Control of environmental parameters inside a smart μ GH

In this study, the decision-making process is based on the following cyber-physical model:

$$D \rightarrow S \rightarrow A, \quad (1)$$

where $D = \{d_1, d_2, d_3, d_4, d_5\}$ represents a set of sensor measurements (d_1 : light intensity from the LDR; d_2 : temperature from the DS18B20 sensor; d_3 : soil moisture from the YL-69 sensor; d_4 and d_5 : ambient air temperature and humidity from the DHT11 sensor), $S = \{s_1, s_2, s_3\}$ denotes a set of control scenarios based on single-input hysteresis, and $A = \{a_1, a_2, a_3\}$ defines a set of actuator control actions (a_1 : LED grow lights; a_2 : USB heaters; a_3 : water pump).



Figure 5. Installation of the DS18B20 temperature sensor, YL-69 soil moisture sensor, and two LED grow lights inside a smart μ GH

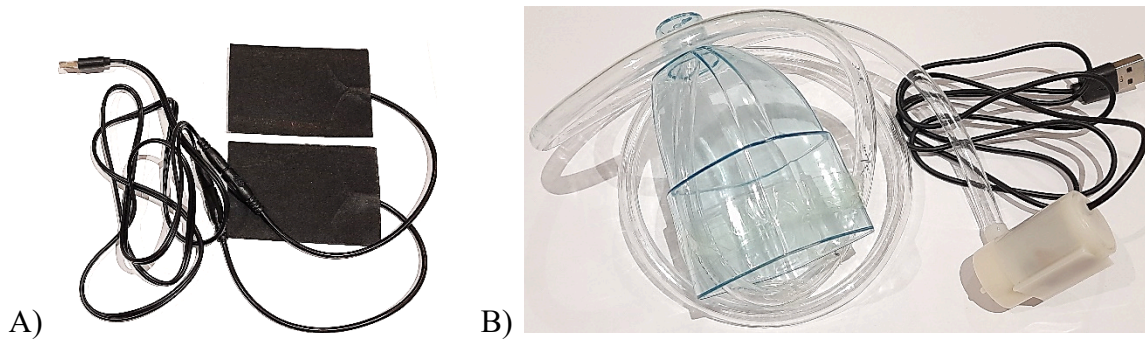


Figure 6. Two portable 5V USB heaters (A) and a 5V diaphragm submersible water pump with water funnel (B), used in the project

The smart μ GH energy system employs high-power consumption equipment, including heaters, artificial lighting, and water pumps. The system regulates actuator timing based on live environmental information to minimise the total energy use (Soussi et al., 2025; Kouadria et al., 2025). Total energy consumption (E) for a given operational cycle is defined as follows (Venkataramanan et al., 2025):

$$E = \sum_{i=1}^n (P_i * t_i), \quad (2)$$

where E represents total energy consumption (Wh), P_i denotes the power consumption of actuator i (W), t_i represents the operating time of actuator i (expressed in minutes), and n is the number of actuators active during the operational cycle ($n = 3$ in this study).

4. Experimental Setup

The experiment was conducted using two micro-greenhouses (μ GHs), each measuring $30 \times 26 \times 20$ cm, with and without IoT equipment (see Figure 2), at an elevation of approximately 800 m in Bishkek, Kyrgyz Republic. Eight previously described plant species were included in the experiment: dill, garden strawberry, lettuce, stock, basil, parsley, sorrel, and spinach. Initially, the seeds were soaked in water for three days (see Figure 7). Seeds were planted in flowerpots containing peat and fertilised soil, after which data were collected from the two micro-greenhouses between 6 and 15 January 2026.



Figure 7. Seeds of spinach, parsley, basil, stock, lettuce, garden strawberry, sorrel, and dill, arranged from left to right and top to bottom, soaking in water

Plant grow lights were OFF during the nighttime, providing plants with a necessary dark period for respiration and nutrient redistribution and avoiding stress-related issues.

The power consumption was measured using USB multimeters KCX-017 (see Figure 8). To display the μ GH environmental parameters to the human expert, the software was developed using an HTML website with clickable buttons to navigate among facilities (see Figure 9) and the C++ sketches for supervisory control of NodeMCU ESP8266 boards and data acquisition from them (see Figure 10).



Figure 8. An example of the USB multimeter KCX-017 usage in the experiment

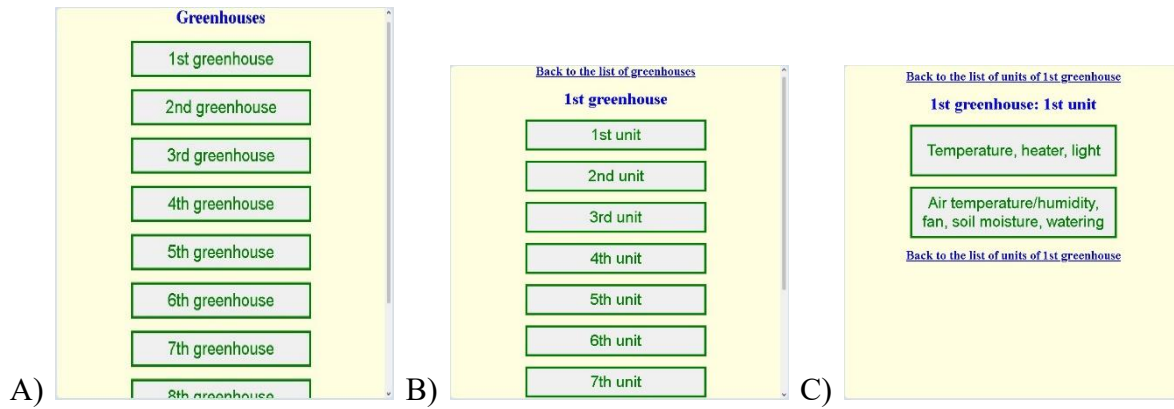


Figure 9. HTML website for the navigation among facilities: an example of a webpage with a list of greenhouses (A), an example of a webpage with a list of units inside the 1st greenhouse (B), and an example of a webpage with a list of NodeMCU ESP8266 boards inside the 1st unit of the 1st greenhouse (C)

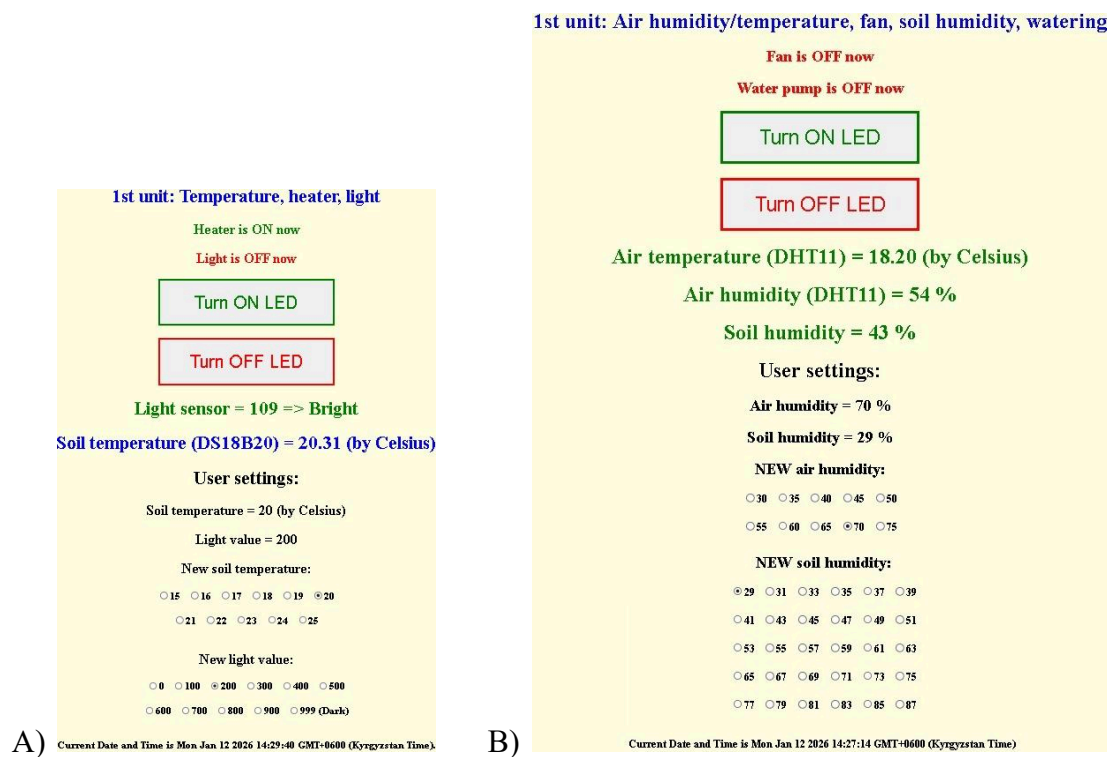


Figure 10. An example of the data received from the 1st (A) and the 2nd (B) NodeMCU ESP8266 boards on January 12, 2026

5. Results

Figure 11 presents the air temperature inside (solid line, DS18B20 sensor) and outside (dashed line, DHT11 sensor) the smart μ GH. The experiment commenced at 10:30 am on 6 January 2026 and concluded at 10:00 am on 16 January 2026, with a total duration of 14,370 minutes. Analysis of the data presented in Figure 11 shows that IoT equipment controls the air temperature inside the μ GH according to the value defined by the human expert (20⁰C in this experiment). Sometimes, the air temperature inside the μ GH does not reach the defined value because of the low ambient air temperature outside a μ GH and low-power portable heaters installed below a μ GH. These values are sent to NodeMCU ESP8266 boards via HTTP GET requests with URL parameters, and they are stored on the Flash memory using SPIFFS (Serial Peripheral Interface Flash File System) (Pan et al., 2022). In this study, the standard Wi-Fi protected setup with passwords is employed to secure wireless connections among network nodes (Chatzisoifroniou & Kotzanikolaou, 2025).

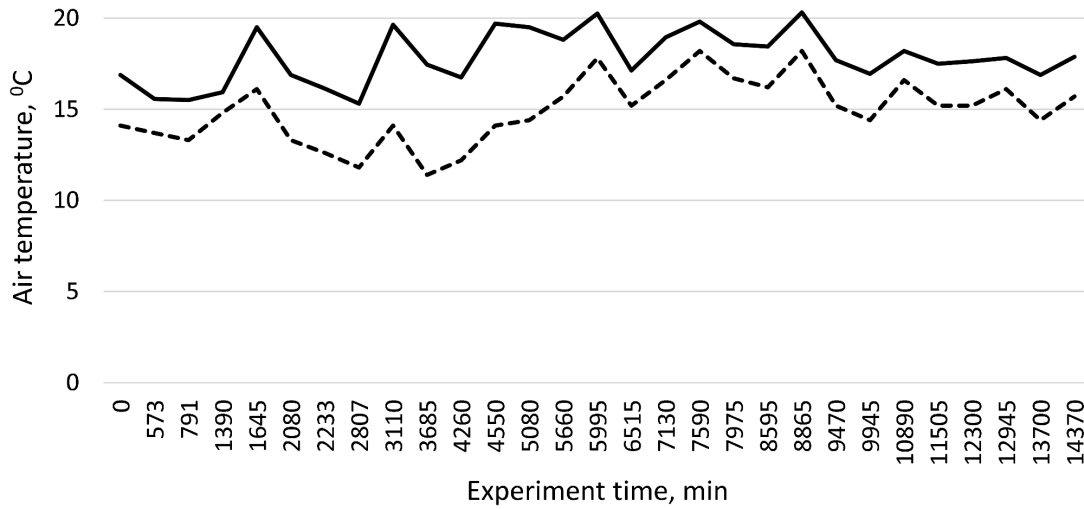


Figure 11. Air temperature inside (solid line, DS18B20 sensor) and outside (dashed line, DHT11 sensor) a μ GH

Figure 12 presents the power consumption of the μ GH with IoT equipment (solid line) and without it (dashed line). The data in Figure 12 show that the smart μ GH consumes less power than the μ GH without IoT equipment. The total energy consumption (E , Equation 2) in the two configurations was 1614.7 Wh (with IoT equipment) and 1624.0 Wh (without IoT equipment). The standard deviation of a sample (the difference between two time series in this study) was 7.5W. The percentage change for two time series, excluding the sample absolute deviations greater than 7.5W, varies from -0.92% to -5.78% during the experiment. Calculation of the Pearson correlation coefficient (Ajani et al., 2023) with a value of over 0.999 demonstrates a strong positive linear relationship, indicating that both μ GHs consume energy in a synchronised manner. The smart μ GH achieves reduced power consumption by minimising the use of plant grow lights and heaters.

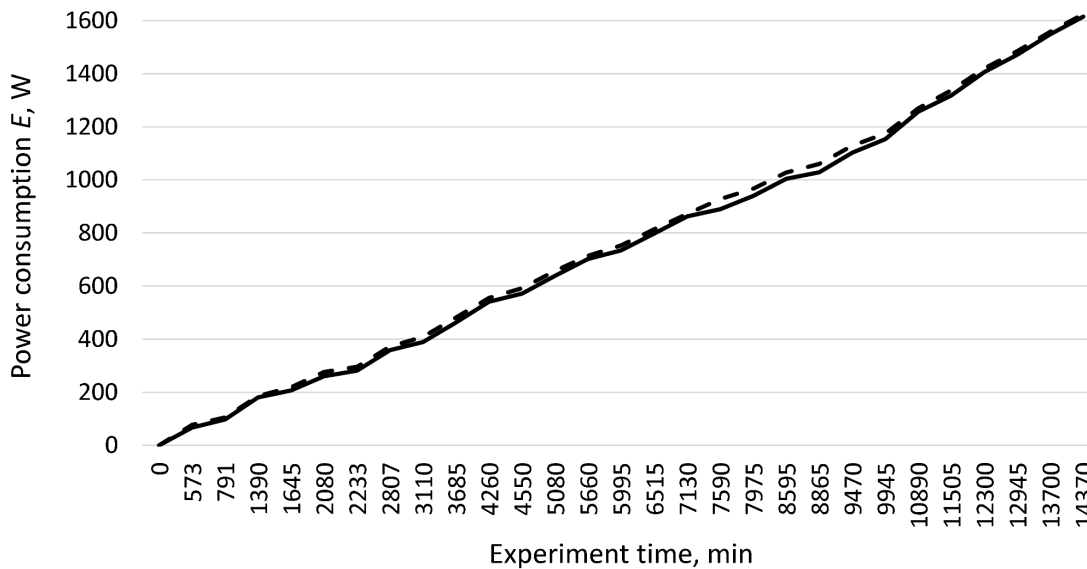


Figure 12. Power consumption E of the μ GH with smart IoT equipment (solid line) and without it (dashed line)

Considering the affordable price (approximately USD 10) of the IoT kit (two NodeMCU ESP8266 boards, four 3V relays, and sensors DS18B20/DHT11/LDR/YL-69) and the possibility of user-friendly supervisory control and data acquisition, the smart μ GH is the preferred solution. In addition, observational findings indicate that six plant species (excluding basil and garden strawberry) exhibited slightly accelerated growth in the smart μ GH during the experiment (see Figure 13; labelled flowerpots correspond to the smart μ GH). The size of a μ GH appeared to be a limitation for the experimental duration – plants started touching the watering system within 10 days. This result demonstrates that the controlled microclimate inside a smart μ GH provides a more favourable environment for early development, which is consistent with Iyaomolere et al. (2025). Overall, the results confirm that the implemented sensing and control system effectively creates a favourable microclimate that supports plant growth during the experimental period.

Figure 14 shows the YL-69 sensor with corrosion at the end of the experimental period, which is consistent with Aziz et al. (2025) – capacitive soil moisture sensors provide long-term stability and corrosion resistance compared to exposed metal resistive probes, such as YL-69. Also, Figure 14 presents an example of the recommended capacitive soil moisture sensor.

6. Discussion

In this study, a novel smart micro-greenhouse (μ GH) prototype is designed to provide a controlled environment for early plant development. The power consumption of a smart μ GH is lower than that of the μ GH without IoT equipment. However, the selection of hardware and software components, as well as control algorithms used in the prototype, is empirical and therefore open to further discussion.

During an interdepartmental workshop involving the University of Central Asia and Kryvyi Rih National University, several technical concerns were raised regarding the optimisation and scalability of the system. While these observations provide important context, they do not invalidate the core findings of this study. Regarding the further minimisation of power consumption, Convolutional Neural Networks were suggested to optimise lighting and irrigation cycles through predictive modelling (Zhao et al., 2024). Similarly, the inclusion of additional sensors, such as pH, was recommended to provide more data for human experts to analyse (Dewi et al., 2026). The short experimental duration (10 days) and the use of a single soil moisture sensor per prototype may limit the information from different plants. Furthermore, the empirical threshold selection and the absence of repeated trials or quantitative biomass measurements (e.g., stem height and leaf count) are noted as limitations.

Nevertheless, as a proof-of-concept focused on power analysis and cost-effectiveness, the current results remain robust. These points of discussion serve as a valuable roadmap for future iterations, where precise biological metrics and advanced AI-driven control algorithms are planned to improve the smart μ GH.

7. Conclusions

This study presents the results of the first stage of the “COMMON Initiative: Climate-Smart Agriculture Demonstration Plot” project funded by the University of Central Asia – a prototype of smart μ GH developed using the IoT equipment (two NodeMCU ESP8266 boards, four 3V relays, and sensors DS18B20/DHT11/LDR/YL-69) to create a comfortable environment for early development of plants. The control algorithm employs a one-input hysteresis with a neutral zone to automatically control the light and temperature inside a μ GH. Data on internal temperature and soil moisture, as well as external temperature, humidity, and light intensity, are provided to the human expert to support the decision-making process on plants’ watering. The experiment with eight plants in two μ GHs demonstrates that the power consumption is slightly less in the smart μ GH than in the μ GH without the IoT equipment. The percentage change between the two time series (with and without IoT equipment) ranged from -0.92% to -5.78% during the experiment, thereby

demonstrating proof of concept for reduced power consumption through optimised use of heaters and plant grow lights.

This study also presents the scaling-up methodology, where a smart μ GH is a unit inside a greenhouse with several units, and a greenhouse is a part of a greenhouse complex. To visualise environmental parameters, an Arduino-based software system was developed, incorporating an HTML interface for navigation and C++ programs for supervisory control of NodeMCU ESP8266 boards and data acquisition.

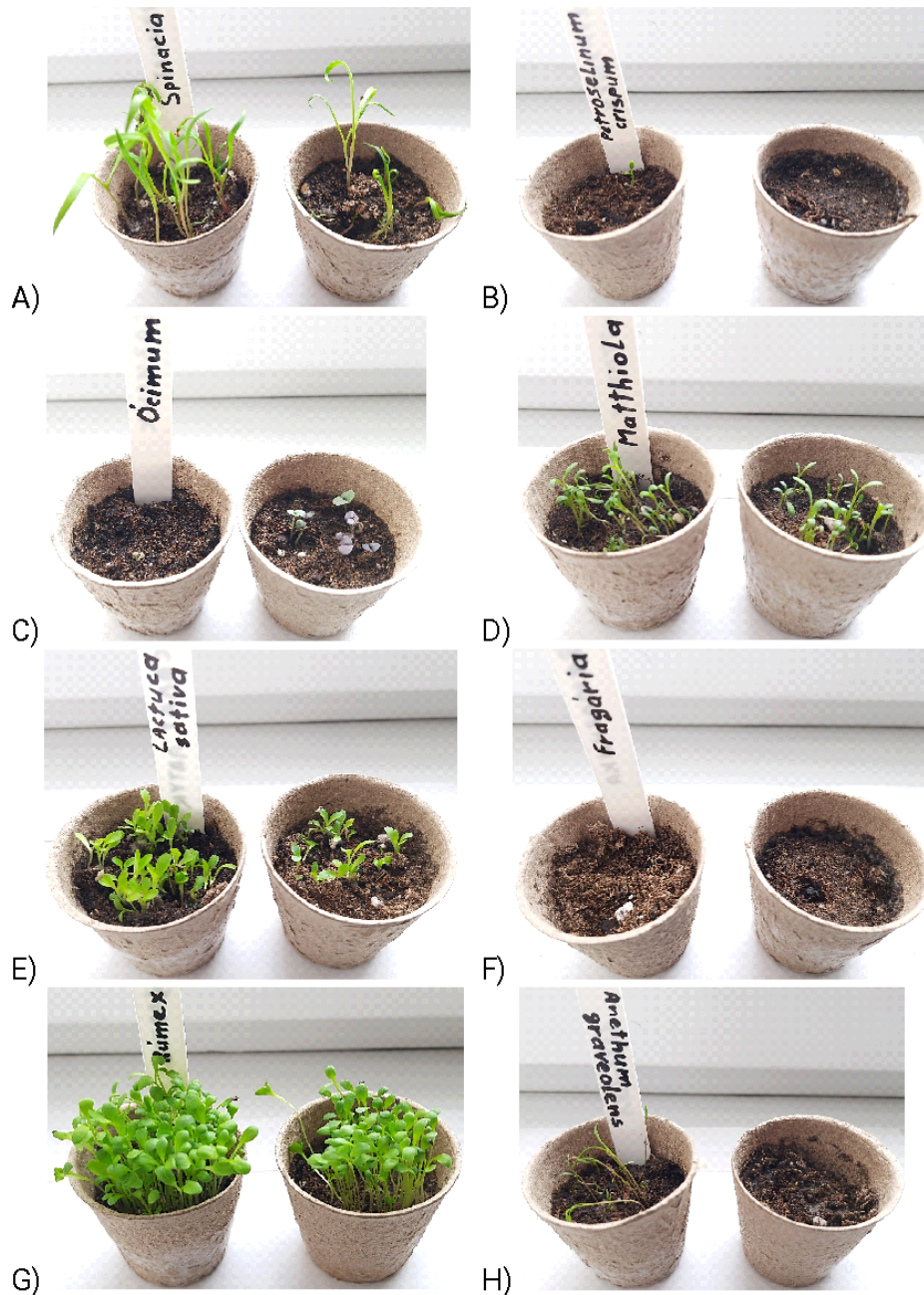


Figure 13. Spinach (A), parsley (B), basil (C), stock (D), lettuce (E), garden strawberry (F), sorrel (G), and dill (H) at the end of the experimental period (flowerpots with labels are from a smart μ GH)

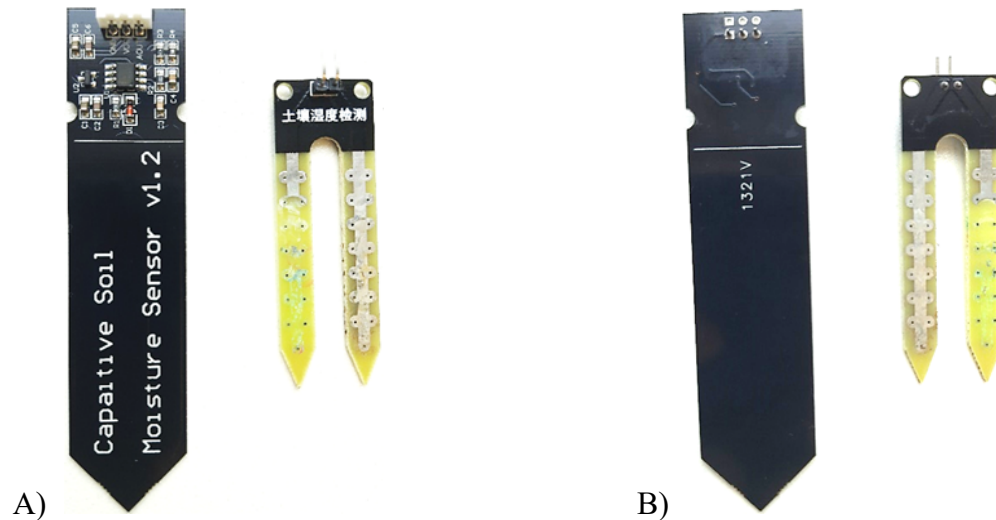


Figure 14. YL-69 sensor at the end of the experimental period (on the right) and an example of the capacitive soil moisture sensor (on the left): frontal (A; the corrosion is on the left side of the YL-69 sensor) and back (B; the corrosion is on the right side of the YL-69 sensor) views

In the next stage of this project, the machine learning algorithm will be employed to minimise power consumption.

Two most likely prospects in developing this study are the use of a convolutional neural network to minimise power consumption and the employment of additional sensors, such as pH, to improve the quality of recommendations provided to human experts.

8. Acknowledgements

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9. Declaration on Generative AI

In preparing this work, the authors employed the Grammarly writing assistant Phuangsuwan et al. (2024) for grammar and spelling errors, as well as the Gemini generative AI chatbot to discuss the results of the study. Following the use of these tools, the authors reviewed and edited the content. The authors take full responsibility for the content of this publication.

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