International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

Applying Artificial Intelligence (AI) and the Internet of Things (IoT) in designing smart plant care systems

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International Journal of Science and Research Archive, 2026, 19(01), 277-287

Publication history: Received on 27 February 2026; revised on 05 April 2026; accepted on 07 April 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.19.1.0696

Abstract

The decline in the labor force and the negative impacts of climate change are posing severe challenges to the agricultural sector. This study presents the design and evaluation of a closed-loop plant care ecosystem applying the Internet of Things (IoT) and Artificial Intelligence (AI). The system utilizes a network of microclimate and capacitive soil moisture sensors to collect real-time data, synchronized via the WebSocket protocol. The focus of the research is the integration of an AI deep learning model for pest identification via an AI Camera and the application of a fertigation system to optimize nutrition. Experimental results show that the system can save up to 80% of water consumption, reduce irrigation labor costs by 90%, and achieve an accuracy of over 80% in pest and disease identification. The research provides a viable solution, ranging from low-cost automation (DIY) scale using ESP32 to industrial scale using PLC S7-1200, contributing to the promotion of a precision and sustainable agriculture model.

Keywords: Precision Agriculture; AIoT; ESP32; PLC S7-1200

1. Introduction

The agricultural sector globally and in Vietnam is at a crossroads with dual challenges. Climate change with extreme weather phenomena such as El Nino has caused severe droughts, especially in the Central Highlands and South Central Coast regions, severely depleting water resources. Simultaneously, the economic restructuring has led to a severe shortage of agricultural labor, with a recorded decline rate of up to 37.2% over the past decade.

To solve this problem, the transition from traditional, intuition-based farming methods to plant data management (Precision Agriculture) is an inevitable trend. However, current greenhouse systems mostly only use rigid, rule-based control logic according to fixed thresholds, lacking flexible "awareness" of microclimate variations.

Nevertheless, most current solutions still have three core limitations: (1) Complete reliance on Cloud connection for AI data processing, leading to the risk of system paralysis during network outages; (2) Expensive real-time API maintenance costs ; and (3) Frequent use of low-level microcontrollers, which struggle to meet electromagnetic interference (EMI) resistance requirements when scaled up to large industrial farms.

Therefore, this study proposes the design of a comprehensive AIoT system that not only automates irrigation but also acts as a digital "plant doctor", using computer vision to diagnose diseases and make personalized care decisions. By exploiting a large language model (Google Gemini) to train a Local AI Edge network, the system thoroughly solves the latency problem, providing an Offline Fallback autonomous mechanism with a 24-hour forecast. Furthermore, the parallel combination of the ESP32 microcontroller for civil use and the PLC S7-1200 for industry creates a smart agricultural solution with high inheritability and commercialization potential.

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Table 1 Comparison of the proposed system with global AIoT studies

Analysis Criteria	Recent International Research Trends	Proposed System Architecture	Competitive Advantage of the Proposal
Microprocessor Platform	Primarily limited to the microcontroller level such as Arduino Uno, Raspberry Pi, or ESP32	Flexible integration between ESP32 (Civil) and PLC S7-1200 (Industrial)	Ready for technology transfer to large-scale farms.
Resource Saving Efficiency	Water-saving capacity ranges from 50.84% to 61%	Ranges from 50% - 80% with an automated fertigation system	Efficiency is equivalent to high academic standards but with lower constituent costs.
AI Operating Mechanism	Image processing using CNN, continuously pushing data to the cloud server	Utilizes an internal AI model combined with a 24h forecasting scenario	Capable of uninterrupted Offline Fallback autonomy.

2. Materials and system architecture

The system architecture is built according to the standard 4-layer IoT structure, operating on a closed-loop feedback mechanism.

2.1. Data Collection Layer (Sensor Network)

To ensure durability in a wet soil environment, the system uses capacitive soil moisture sensors instead of resistive ones to prevent oxidation and measure the dielectric constant of the soil. The microclimate is monitored by the SHT20 temperature-humidity sensor and the TEMT6000 light sensor (IC from Vishay), which allows the conversion of light intensity into linear Analog voltage. In addition, a raindrop detection sensor is integrated to automatically shut off the irrigation cycle when the weather changes.

2.2. Edge Computing Layer and Actuators

- Civil (DIY) scale: Uses the ESP32-WROOM-32 microcontroller as the central brain due to its built-in WiFi/Bluetooth, processing speed of up to 240MHz, and 520 KB of SRAM.
- Industrial scale: Proposes the use of the Siemens S7-1200 Programmable Logic Controller (PLC) to ensure high electromagnetic interference (EMI) resistance. The system applies the mathematical functions NORM_X and SCALE_X on the TIA Portal V17 platform to normalize the Analog signal range (0-27648) from industrial sensors.
- Actuators: Includes optical isolation Relay modules to control the pressure pump, ventilation fan, and quantitative fertigation system.
- When the ESP32 or PLC S7-1200 loses its Wi-Fi/Internet connection with the Server, the edge device will automatically switch to running a pre-loaded offline scenario (Local Control) to prevent the plants from drying out.

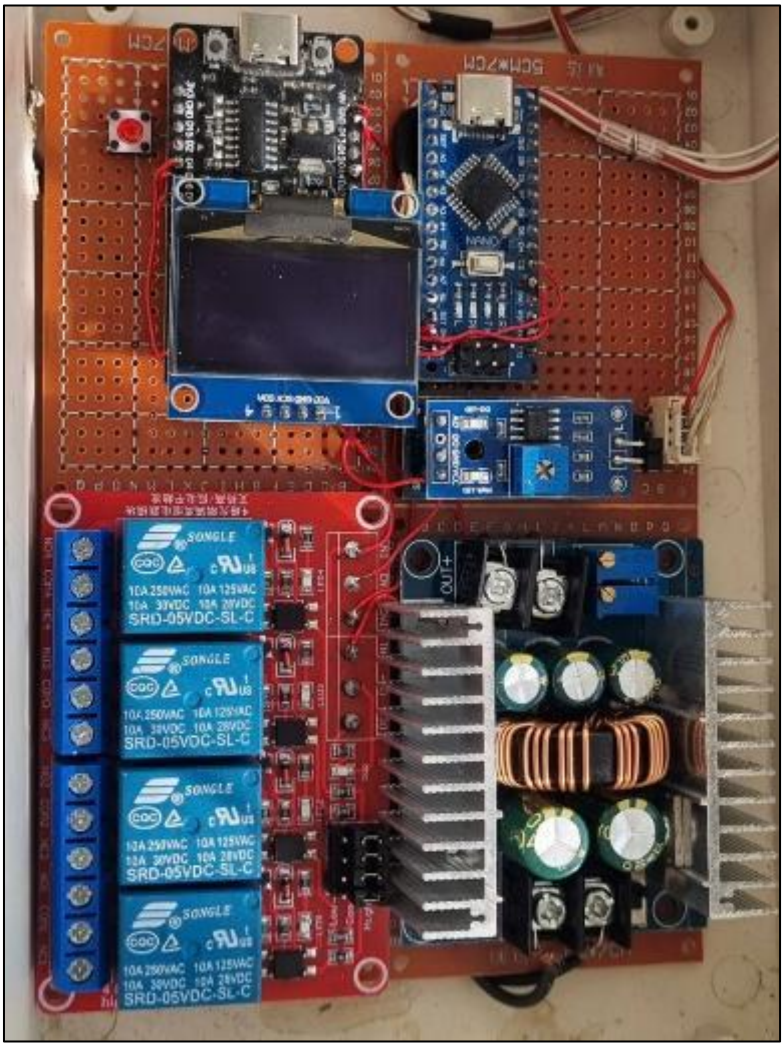

Figure 1 Central processing unit of the experimental model

Table 2 Main components of the central processing unit of the greenhouse model

Component	**Function**
1.3-inch OLED display with I2C communication	Screen displaying the system's status and working mode
ESP32 Wifi + Bluetooth CH340	Receives, processes, and transmits data to the Server
Arduino Nano	Receives signals from the Server and issues commands to the relay
4-Channel Relay Module	Executes commands from the control module
Temperature sensor module	Transmits real-time temperature data to the Server
Light sensor	Transmits real-time light data to the Server
Soil moisture sensor	Transmits real-time soil moisture data to the Server
Water drop sensor	Transmits real-time raindrop detection data to the Server
Buck converter circuit	Converts 12V to 5V for control modules
12V Switching Power Supply	Provides power for lights, fans, pumps, heaters, and buck converter circuits

2.3. Automatic Fertigation Technology

The research applies image analysis of the plant's condition analyzed by the system. Subsequently, it adjusts the ratio of fertilizer mixed into the irrigation water suitable for the plant. This ensures that nutrients are delivered directly to the plant roots through a drip irrigation network.

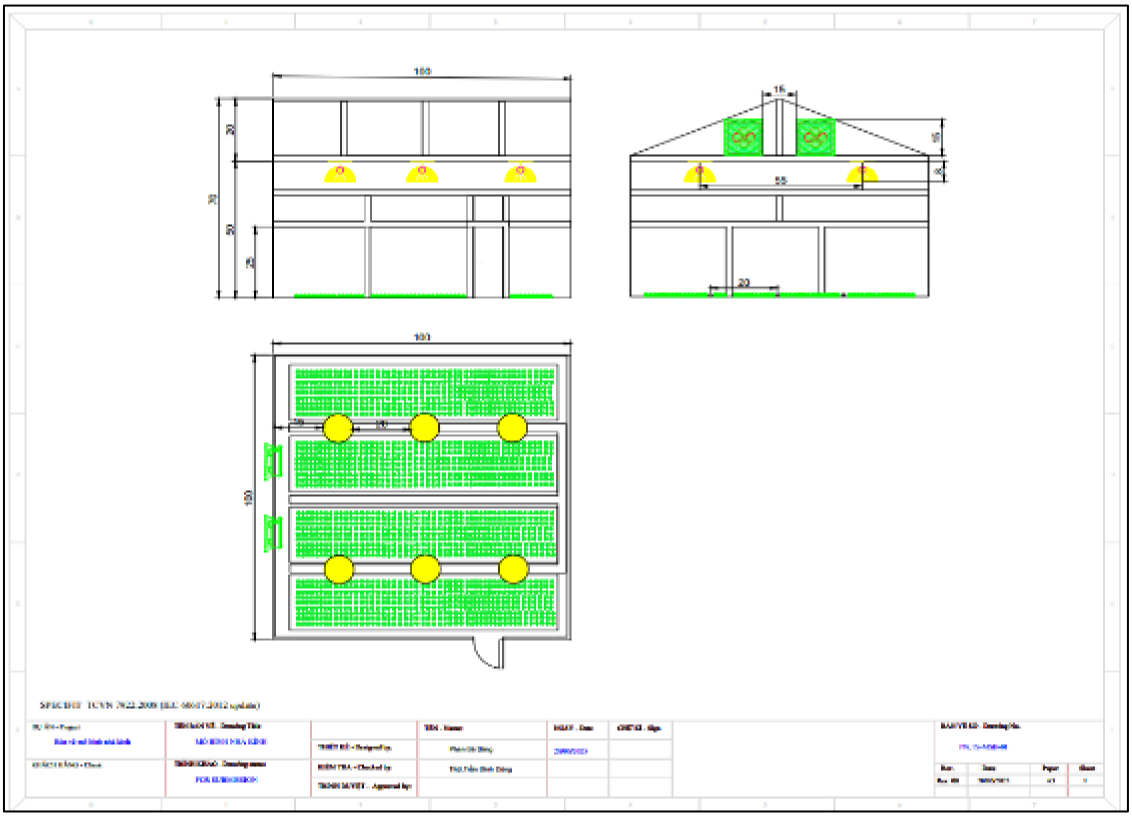

Figure 2 Greenhouse drawing used in the research model

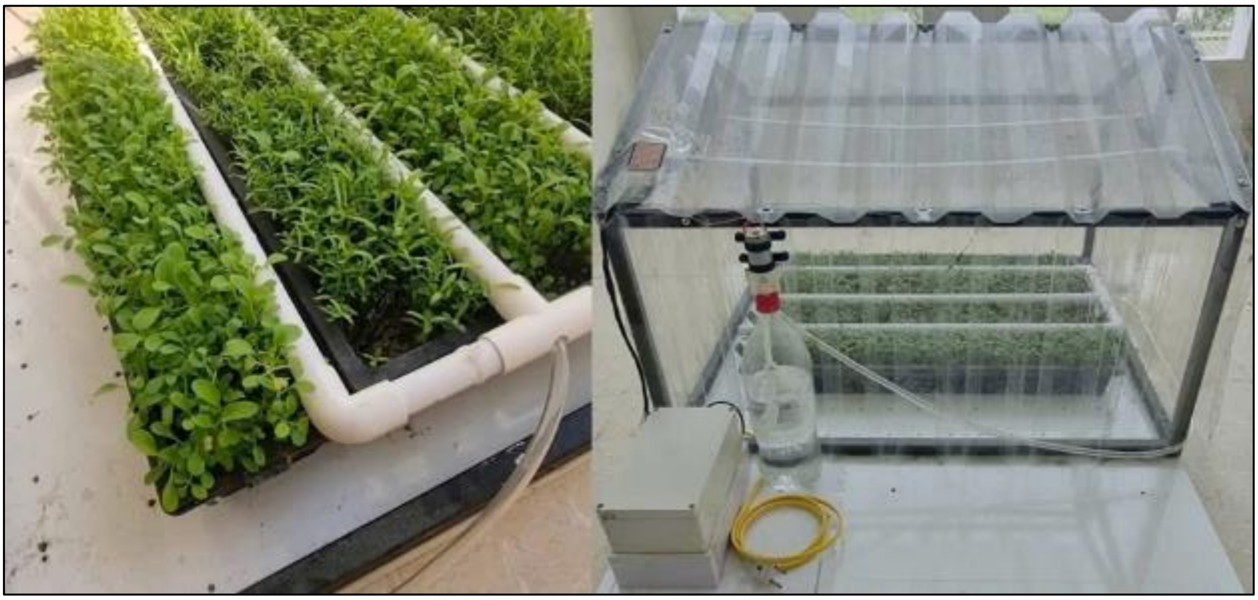

Figure 3 Smart greenhouse model in the laboratory

2.4. Industrial Scale Proposal (Scale-up Design)

To solve the problem of practical application in a large space scale (1000m^2 greenhouse), the study designed an industrial electrical cabinet system using the Siemens S7-1200 Programmable Logic Controller (PLC) combined with an HMI KTP1200 screen.

- Lighting: Calculated using DIALux evo software with 76 Philips GreenPower LED toplighting compact lamps, total luminous flux of 357,142 lm, ensuring a standard illuminance of 14,000 Lux.
- Ventilation and Heating: Selection of industrial fans with a flow rate >2016 m^3/h to meet the air exchange rate of 60 times/hour, combined with a 3kW hot air drying fan.
- PLC Algorithm: Uses the NORM_X and SCALE_X functions on the TIA Portal V17 platform to normalize the Analog signal range (0-27648) from industrial sensors before issuing commands to activate the Contactor.

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3. Artificial intelligence (AI) integration method

3.1. Cloud Synchronization and Storage

Microclimate data is continuously transmitted to the Web Server via the WebSocket protocol with SSL encryption, enabling parameter updates to the Dashboard with extremely low latency.

3.2. Computer Vision in Pest Diagnosis

The system applies a Convolutional Neural Network (CNN) deep learning model, specifically an advanced AI Camera architecture. This model is capacity-optimized to run on embedded systems while retaining robust feature extraction capabilities. AI analyzes images from surveillance cameras to identify dangerous pest and disease targets right from their onset.

3.3. Smart Decision Making

The server calls APIs of large language models (such as Google Gemini) to analyze cross-environmental datasets, thereby outputting warnings or device control scenarios (e.g., turning on the fan when the temperature exceeds the optimal threshold).

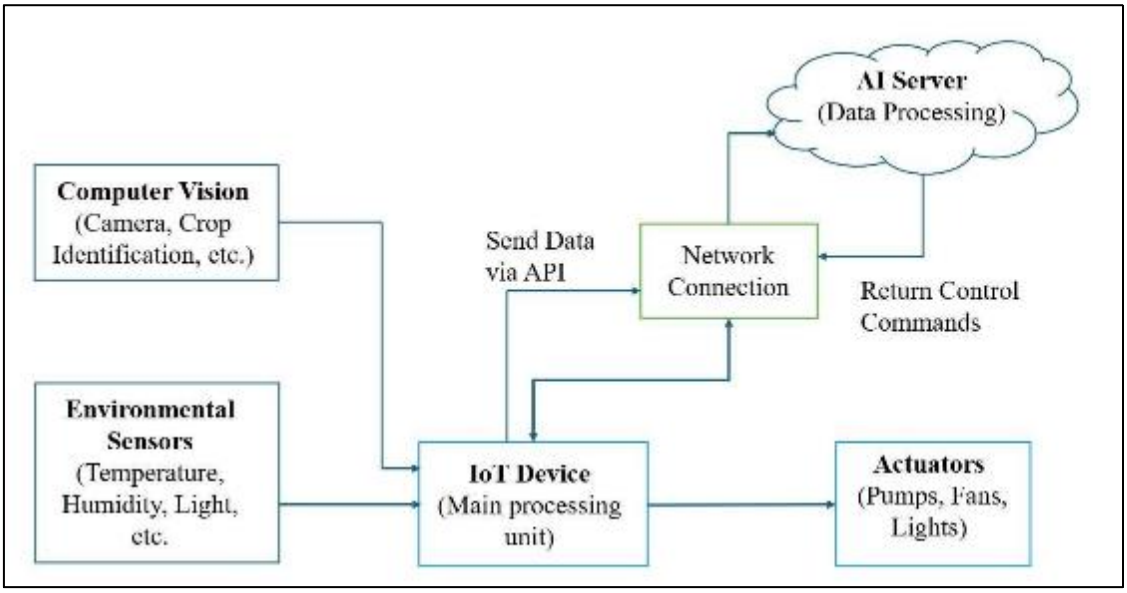


Figure 4 Operational structure of the system

In terms of smart applications, the web-based Dashboard interface allows users to manage multiple cultivation spaces and monitor parameters in real-time. Specifically, the server is programmed to call Google's Gemini API to process complex datasets. This combination aims to analyze growth images combined with environmental parameters to automatically diagnose plant pathologies in the future.

4. Research methods and results

4.1. Evaluation of the Experimental Model

4.1.1. Online Operating System

The hardware system has been completely assembled and tested on a laboratory scale. The central processing unit operates stably, maintaining Wi-Fi connectivity and a successful automatic reconnection mechanism (Heartbeat) with the WebSocket server.

Table 3 Experimental operational results and system accuracy

Parameter	Actual Measurement Range	Device Error	Response Latency	AI Confirmed Status
Ambient Temperature	19°C – 32°C	± 0.3°C	< 500ms	Optimal (Normal)
Soil Moisture	40% – 85%	± 2%	< 500ms	Pump Activated (< 60%)
Light Intensity	0 – 15,000 Lux	± 5%	< 700ms	LED Light Activated
Cloud Connection	99% Uptime	Heartbeat: 30s	Average 1.2s	Stable operation

4.1.2. Offline Reliability Testing

To evaluate the availability and Fault Tolerance of the edge control system, the study conducted a simulated Internet disconnection experiment for 24 hours. The goal of the test was to verify whether the ESP32/PLC device could maintain automatic irrigation operations based on soil sensors and locally saved 24h forecast scenarios, or if it would fall into a system hang state upon failing to receive API responses.

Procedure method:

- T=0: The system is operating normally in the Online state. The weather forecast scenario and irrigation process for the next 24 hours have been synchronized by the internal AI model down to the edge device.
- T=1h to T=24h: Proceeded to completely disconnect the Wi-Fi router providing the network for the greenhouse area. The Web Server and API are completely unreachable.
- Parameters regarding soil moisture and the history of water pump Relay activations are saved locally by the device (or recorded via an independent offline measuring device) for verification once the network is restored.

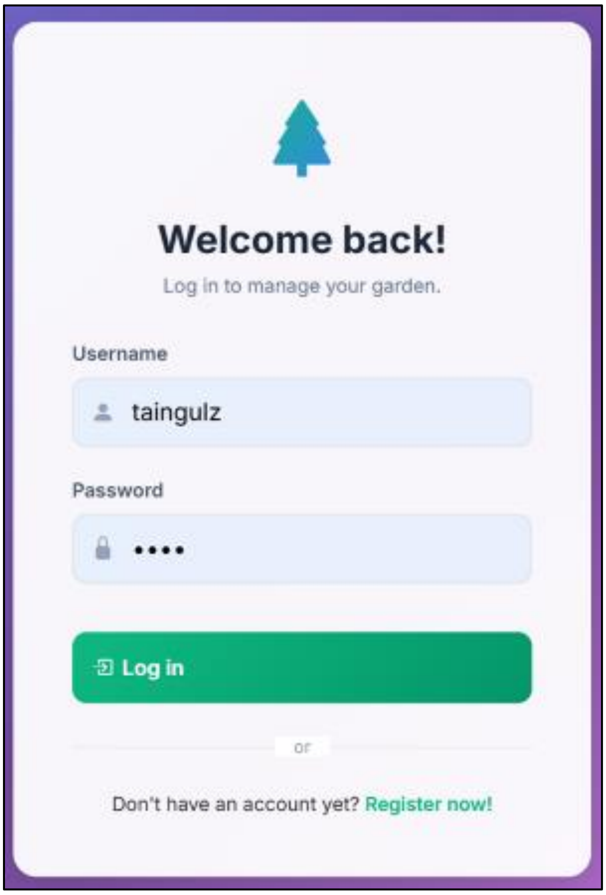
Table 4 System activity log during 24 hours of Internet disconnection

Network Outage Time	Measured Soil Moisture	Internal Setting Threshold	Pump Relay Activity	System Status
Hour 1 (08:00)	75%	Activate below 60%	Pump off	Awaiting local command
Hour 5 (12:00)	58%	Activate below 60%	Pump automatically turns on for 1 min	Independent operation (Offline)
Hour 6 (13:00)	68%	Safe threshold reached	Pump off	Independent operation (Offline)
Hour 15 (22:00)	62%	Activate below 60%	Pump off	Independent operation (Offline)
Hour 20 (03:00)	55%	Activate below 60%	Pump automatically turns on for 1 min	Independent operation (Offline)
Hour 24 (07:00)	70%	Wi-Fi connection restored	Synchronize data log to Server	Smooth return to Online

The experiment showed that when the network connection was completely lost, the hardware system was not hung or disabled. The central microcontroller immediately switched to Local Autonomous Mode, using previously pre-loaded forecasting parameters combined with real-time signals from the soil moisture sensor to make actuation decisions. Throughout the 24 offline hours, the pump was still accurately activated (2 times) when the soil moisture dropped below the allowable threshold, ensuring the plants did not lack water. Upon network restoration, the system automatically reconnected (Reconnect) and pushed all historical operational data to the synchronization server, confirming the high stability of the proposed AIoT architecture.

4.2. Software and User Interface Evaluation

The SmartTree AI Dashboard management interface operates smoothly on the web platform. The Dashboard continuously updates actual parameters: soil moisture, ambient temperature, rain status, and light intensity. The status of control Relays (Water Pump, Ventilation Fan, Light, Heater) is also accurately synchronized between hardware and software. The system's recording and exchange of data with the Google Gemini API initially opens up the possibility of establishing highly personalized plant care protocols, completely replacing traditional rigid timer-setting cycles.



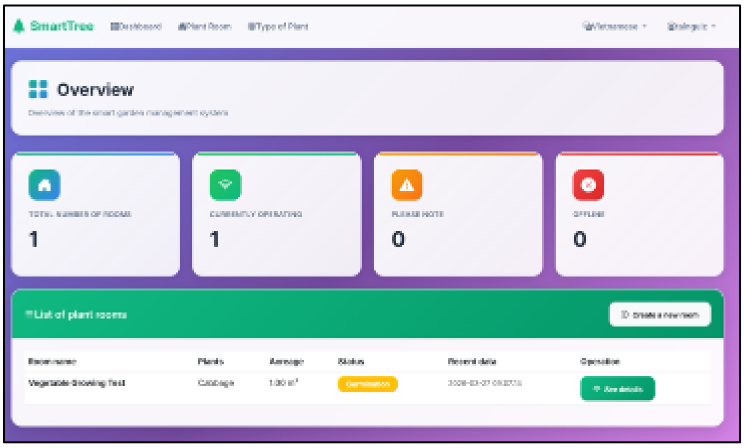
Welcome back!

Log in to manage your garden.

Username: taingulz

Password: ••••

Figure 5 Login frame for the Web Server



Room name	Plants	Acreage	Status	Record date	Operation
Vegetable Growing Test	Cabbage	1.00 m²	[illegible]	[illegible]	See details

Figure 6 Administration page

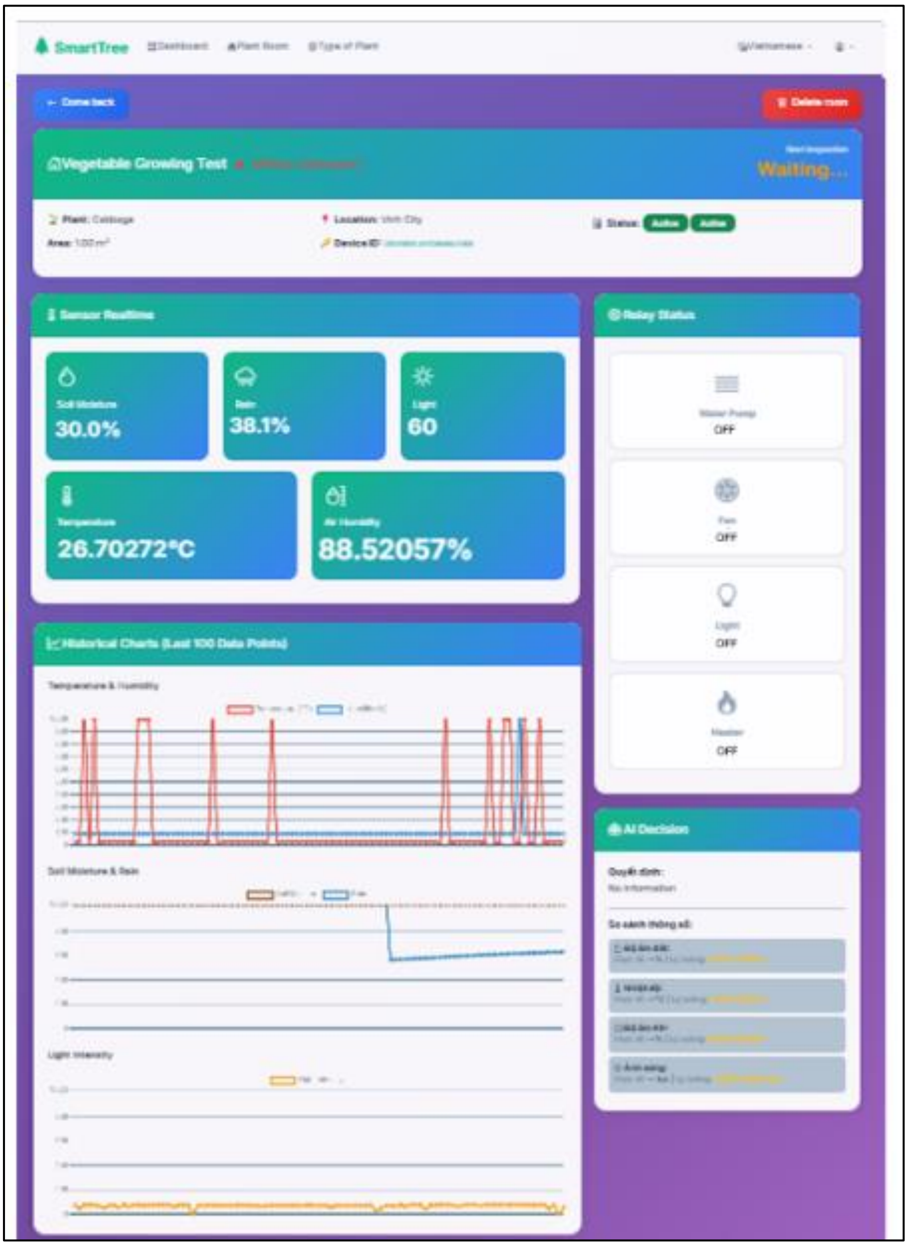


Figure 7 Interface of the Web Server ” https://dash-smtree.ziang.me”

4.3. Performance of Water and Nutrient Resource Optimization

Experiments show that the closed-loop feedback mechanism operates effectively. The combination of soil moisture and rain sensors helps the system automatically eliminate redundant pumping cycles. Comparative results record that the system saves up to 50% - 80% of water consumption compared to manual irrigation methods. Concurrently, the fertigation method combined with drip irrigation completely prevents fertilizer runoff, protecting the groundwater environment and increasing the absorption efficiency of the root system.

To accurately evaluate the performance of water resource optimization, the study arranged a Control Experiment under standard greenhouse conditions. The test area was divided into two independent mustard greens planting beds, with the same area ($1m^2$), the same type of substrate, and subject to identical climatic conditions.

- Control Group (Beds 1,2): Applied traditional manual irrigation methods. Plants were irrigated periodically twice a day (morning and evening) with a fixed volume based on sensory experience.

- Experimental Group (Beds 3,4): Applied the designed automated AIoT irrigation system. The water pumping cycle was completely automatically controlled based on a closed-loop feedback algorithm from the soil moisture sensor (activated when moisture < 60% and turned off when reaching the optimal threshold) combined with the shut-off condition of the raindrop sensor.

The monitoring process was conducted continuously throughout one plant growth cycle (30 days). End-of-period consolidated data shows that, thanks to completely eliminating redundant irrigation cycles on days with high humidity or rain, the AIoT system significantly minimized water waste, saving from 50% to 80% of total water volume compared to periodic manual irrigation methods.

Table 5 Comparison of water consumption between manual irrigation methods and the AIoT system over 30 days (Unit: Liters)

Time	Control Group (Manual Irrigation)	Experimental Group (AIoT System)	Water Saved	Saving Efficiency	Microclimate Conditions
Week 1	14.0	5.5	8.5	60.7%	Seedlings, high initial soil moisture
Week 2	14.0	2.5	11.5	82.1%	Heavy rain, sensor triggered to shut off pump
Week 3	14.0	8.0	6.0	42.8%	Hot sun, system increased moisture compensation irrigation
Week 4	14.0	5.0	9.0	64.3%	Cool, stable weather
Total	56.0	21.0	35.0	62.5%	Within the 50% - 80% range

4.4. Accuracy of the AI Model

4.4.1. Online Autonomous Mechanism

The AI Camera model demonstrates high reliability in real-world conditions. Analytical testing on the image dataset achieved an accuracy of over 80% for complex insects and pests (such as brown planthoppers, black bugs). This capability plays a decisive role in establishing a "Digital Twin" model, allowing for real-time crop risk simulation and warning.

4.4.2. Offline Autonomous Mechanism

One of the system's breakthroughs is its Fault Tolerance capability during a complete loss of Internet connection. Because the internal AI model has been trained on the microclimate characteristics of the greenhouse, it has the ability to combine with weather forecast data to pre-program action scenarios.

Operationally, the system continuously pre-loads and interpolates environmental change forecasts for the next 24-hour cycle. In the event of a wide-area network outage making the cloud API inaccessible, the edge control device (ESP32/PLC) immediately switches to Local Autonomous Mode. At this point, the system will use the previously predicted 24h scenario as a reference frame to compare with actual sensors, thereby making accurate decisions to turn on/off actuators. This mechanism ensures the closed-loop care process is not interrupted, absolutely protecting crops during the waiting time for technicians to fix the network issue.

4.5. Economic Efficiency and Expansion Feasibility

For civil scales, the DIY configuration using ESP32 and basic components (Relays, 12V mini pumps, switching power supplies) has a very low investment cost (only about a few hundred thousand to 1 million VND), suitable for apartment balcony gardens. Operationally, the system helps cut more than 90% of labor costs for irrigation activities alone.

Simulations on the TIA Portal platform show that when the simulated temperature rises above 35.5°C or humidity drops below 60%, the PLC S7-1200 immediately closes the contact to activate the cooling fan and pump, confirming absolute responsiveness for large-scale industrial farms. The electrical cabinet layout diagram and greenhouse installation drawings fully meet electrical safety technical standards, ready for practical deployment.

Regarding software operating costs (OPEX), the system achieves a superior commercial advantage thanks to the Edge AI deployment strategy. Specifically, instead of calling the API continuously in real-time - a condition that easily leads to dependency on the transmission line and incurs high costs - the research only utilizes the Free Tier version of Google Gemini. In this architecture, Gemini acts as an expert providing a Knowledge Base to create a Training Dataset. This data is then used to train an internal Local AI Model specifically serving the project. Thanks to shifting the computational workload from the Cloud down to local devices, the project brings external API maintenance costs to 0 VND while simultaneously ensuring absolute security of the plantation's growth data.

5. Conclusion

The study successfully designed and evaluated a comprehensive digital plant care garden ecosystem. By replacing intuitive experience with quantitative data, the combination of IoT, controllers (ESP32/PLC S7-1200), and Artificial Intelligence (AI and Camera AI) has thoroughly solved the problem of labor scarcity and optimized resources (water, fertilizer). In the future, the system has the potential for expansive development by combining with Blockchain technology for transparent agricultural product traceability, as well as integrating Autonomous Robots to perfect a fully autonomous smart farm model.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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