ESTABLISHMENT OF THE LOW-COST GROWTH CHAMBER FOR THE ADAPTIVE DIFFERENTIATION OF LAI CHAU GINSENG (*Panax vietnamensis* var. *fuscidiscus*) IN HANOI

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ABSTRACT

The study aims to establish a low-cost IoT-based growth chamber to facilitate the adaptive differentiation of Lai Chau ginseng (*Panax vietnamensis* var. *fuscidiscus*) in Hanoi. By integrating components such as the ESP32 microcontroller, DHT22 sensor, DS3231 real-time clock, BH1750 light sensor, LED LCD 1602 display, and RS385 water pump, the chamber maintains optimal conditions for ginseng growth. The system features real-time monitoring and control of environmental parameters via a Flutter-based mobile application. This setup ensures precise regulation of temperature, humidity, light intensity, and irrigation, promoting the healthy development of ginseng in low-altitude regions. As expected, our evaluations showed significant improvements in plant height, leaf area, chlorophyll fluorescence, and chlorophyll content under treatment conditions, highlighting the chamber's effectiveness. Future work should optimize the chamber with advanced sensors and automation and expand the mobile app with predictive analytics and machine learning for enhanced growth insights and stress detection.

NGHIÊN CỨU CHẾ TẠO TỦ SINH TRƯỞNG CHI PHÍ THẤP ĐÁP ỨNG VỚI SỰ THÍCH NGHI CỦA SÂM LAI CHÂU (*Panax vietnamensis* var. *fuscidiscus*) TẠI HÀ NỘI

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TỪ KHÓA

Tủ sinh trưởng
Sâm Lai Châu
Tính trạng nông sinh học
Thích nghi
Internet vạn vật

TÓM TẮT

Nghiên cứu này nhằm mục tiêu thiết lập buồng sinh trưởng dựa trên công nghệ Internet vạn vật chi phí thấp để đánh giá khả năng di thực của các cá thể sâm Lai Châu (*Panax vietnamensis* var. *fuscidiscus*) tại Hà Nội. Bằng cách tích hợp các thành phần như bộ vi điều khiển ESP32, cảm biến DHT22, đồng hồ thời gian thực DS3231, cảm biến ánh sáng BH1750, màn hình LED LCD 1602 và máy bơm nước RS385, buồng sinh trưởng duy trì điều kiện tối ưu cho sự phát triển của các cá thể sâm. Hệ thống có tính năng giám sát và điều khiển thời gian thực các thông số môi trường thông qua ứng dụng di động phát triển bằng Flutter. Thiết lập này đảm bảo điều chỉnh chính xác nhiệt độ, độ ẩm, cường độ ánh sáng và tưới tiêu, thúc đẩy sự phát triển khỏe mạnh của sâm ở khu vực có độ cao thấp. Kết quả cho thấy sự cải thiện đáng kể về chiều cao cây, diện tích lá, huỳnh quang diệp lục và hàm lượng diệp lục dưới điều kiện trồng có kiểm soát, chứng tỏ hiệu quả của buồng sinh trưởng. Các nghiên cứu tiếp theo sẽ được thực hiện nhằm tối ưu hóa buồng sinh trưởng với các cảm biến và công nghệ tự động hóa tiên tiến, và mở rộng ứng dụng di động với phân tích dự đoán và học máy để nâng cao hiểu biết về tăng trưởng và phát hiện stress trên cây sâm.

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1. Introduction

Lai Chau ginseng (*Panax vietnamensis* var. *fuscidiscus*) has been commonly known as a rare and highly valued medicinal plant native to the mountainous regions of Vietnam. This particular variety is distinguished by its unique morphological characteristics and potent bioactive compounds, which have garnered significant attention for their therapeutic properties [1]. Traditionally, Lai Chau ginseng has been used in folk medicine to treat various ailments, including fatigue, stress, and immune system deficiencies. Its increasing popularity in modern herbal medicine is largely due to its high content of saponins, which are known for their adaptogenic and anti-inflammatory effects [2]. Specifically, the plant thrives in these high-altitude regions' cool, humid climate, often growing at 1,200 and 1,500 meters above sea level. The native habitat of Lai Chau ginseng is characterized by rich, well-drained soils, abundant organic matter, and a canopy that provides partial shade, similar to the conditions found in the forest undergrowth. Moreover, the roots of Lai Chau ginseng are the most prized part of the plant, containing a high concentration of ginsenosides and other bioactive compounds [3]. These substances have been shown to enhance physical stamina, reduce mental fatigue, and improve overall health [4], [5]. Given the unique characteristics and high medicinal value of Lai Chau ginseng [4], [5], studying this species holds considerable significance.

Optimal growth conditions for Lai Chau ginseng include a combination of specific climatic and soil factors [6]. The plant prefers a cool, moist environment with temperatures ranging from 15 to 25 degrees Celsius. It requires well-drained, loamy soil rich in organic matter and a pH between 5.5 and 6.5. The natural shade provided by the forest canopy is crucial for protecting the ginseng from direct sunlight, which can harm its growth. Additionally, maintaining high humidity levels and consistent soil moisture is essential for the healthy development of the plant [7]. Thus, growing Lai Chau ginseng in low-altitude areas presents several significant challenges. The primary issue is the difference in climatic conditions. Low-altitude regions typically experience higher temperatures and lower humidity levels, which are not conducive to the growth requirements of these ginseng individuals. The plant's sensitivity to heat and its need for a stable, cool environment mean that cultivating it outside its native high-altitude habitat often results in poor growth and reduced potency of the medicinal compounds. Moreover, replicating its mountainous origin's natural shade and soil conditions is difficult in low-altitude areas. The absence of a forest canopy and the need for artificial shading systems add to the complexity and cost of cultivation. Soil composition also plays a critical role; the specific nutrient profile and organic matter content found in the ginseng’s natural habitat are hard to duplicate, leading to suboptimal growth and lower yields. Recently, the utilization of IoT-based growth chambers presents a promising solution to the challenges of cultivating rare herbal plants in low-altitude regions [8]. These advanced agricultural systems, equipped with sensors and automation technology, enable precise control and continuous monitoring of critical environmental parameters, including temperature, humidity, light, soil moisture, and nutrient levels [9]. By replicating the plant’s optimal high-altitude conditions within a controlled environment, IoT-based growth chambers facilitate the acclimation and adaptation of plant individuals to lower altitudes. The data-driven insights from these systems allow for fine-tuning cultivation techniques, ensuring resource efficiency and sustainable practices. This approach not only enhances the potential for successful cultivation in non-native environments but also contributes to the conservation and sustainable use of this valuable medicinal species, ultimately benefiting both local communities and the global market [10].

The purpose of this study was to construct a low-cost IoT-based growth chamber to facilitate the adaptation of Lai Chau ginseng plants in Hanoi. By leveraging advanced IoT technology, this research aimed to create a controlled environment that mimics the optimal growth conditions of Lai Chau ginseng, overcoming the climatic challenges of low-altitude regions. The study focused on designing and implementing a cost-effective solution that monitors and regulates critical environmental parameters, such as temperature, humidity, light, soil moisture, and nutrient levels, to ensure the successful cultivation of ginseng plants outside their native high-altitude habitats.

2. Materials and Methods

2.1. Materials

Lai Chau ginseng plants collected from Sin Ho town, Lai Chau province (22°21′35″N 103°15′02″E) were used as samples for the evaluation. Before collecting, all individuals were carefully validated by using morphological descriptors and molecular markers. However, given the rarity of Lai Chau ginseng, the materials available for this study were limited.

2.2. Methods

- Cultivation of ginseng plants: Lai Chau ginseng plants were grown in the substrates (the humus soil: dry cow manure: coconut fiber ratio of 1:1:1) with minor adjustments as following the local guidelines. All fertilizers (chemical and organic) and pesticides were used following the local recommendation.
- Experimental design: The experiment used a Randomized Complete Block Design with three replicates to ensure statistical validity. Three Lai Chau ginseng individual plants were included in each replicate, totaling nine plants used for the study. These nine plants were used to calculate the descriptors, ensuring a comprehensive analysis of the variability and response of the plants under the conditions tested.
- Collection of environmental parameters: Environmental parameters from the local area were systematically collected. Key environmental parameters relevant to the growth of Lai Chau ginseng, including temperature, humidity, light intensity, and soil moisture, were identified based on local knowledge.
- Construction of growth chamber: The growth chamber was equipped with high-precision sensors to monitor humidity, light intensity, and soil moisture, as previously described [11]. These sensors were integrated into an automated control system to maintain the desired environmental conditions. The chamber's humidity was regulated using humidification devices, while light intensity was controlled through adjustable LED grow lights that imitated natural sunlight patterns [12]. Soil moisture was managed using an automated irrigation system, ensuring consistent hydration levels. All sensors were connected to a central data logger with IoT capabilities, allowing for real-time data collection, monitoring, and remote adjustments via a web-based interface. The growth chamber's design and setup were informed by the environmental parameters collected from the local area and the traditional knowledge of local people, ensuring that the conditions closely replicated the ginseng's natural habitat.
- Observation of plant height: An experimental setup with two groups was established to observe the growth of Lai Chau ginseng plant height. The experimental group was placed in an IoT-based growth chamber, maintaining optimal humidity, light intensity, and soil moisture conditions. The control group was placed under an air conditioner, providing regulated temperature without precisely controlling other parameters. The height of the Lai Chau ginseng plants in both groups was measured 10 days each time using a calibrated ruler.
- Observation of leaf area: The leaf area of ginseng plants in both groups was measured 10 days each. Leaf images were captured using a high-resolution camera (iPhone 15 Pro, Apple, USA) and analyzed using ImageJ software [13] to quantify the leaf area accurately.
- Determination of chlorophyll fluorescence and chlorophyll content: The chlorophyll fluorescence of photosystem II (ChlF) was calculated as previously described [14]. Particularly, the fresh leaf was randomly selected from the observed plants to determine the rate of variable fluorescence (Fv) and maximum ChlF yield (Fm) values [15] by using OS-30 (Opti-Sciences, USA) and then collected to determine chlorophyll content by spectrophotometer UV-Vis 2450

(Shimadzu, Japan). The chlorophyll content of Lai Chau ginseng plants was measured 10 days each using the Chlorophyll Meter SPAD-502Plus.

3. Results and Discussion

3.1. Construction of a low-cost growth chamber for the growth and development of Lai Chau ginseng

In order to construct the IoT-based growth chamber, various cheap sensors and modules have been utilized. As a result, an IoT-based growth chamber equipped with an ESP32 microcontroller, DHT22 sensor for temperature and humidity monitoring, DS3231 real-time clock module, BH1750 light intensity sensor, LED LCD 1602 for display, relay module for automated control of environmental parameters, an RS385 water pump for precise irrigation, and LED grow lights to provide optimal light conditions for plant growth (Figure 1).

Particularly, the ESP32-WROOM-32D microcontroller is vital for the IoT-based growth chamber, measuring 18 mm × 20 mm × 3 mm. It features a Dual-Core 32-bit CPU running up to 240 MHz, with 448 KB ROM, 520 KB SRAM, and additional SRAM for deep-sleep operations. It supports 802.11 b/g/n/e/i Wi-Fi and Bluetooth v4.2 and includes various peripheral interfaces, such as a 12-bit ADC, 8-bit DAC, touch sensors, infrared communication, PWM channels, and multiple communication interfaces. Operating at 2.2 - 3.6V with 80mA current consumption, it efficiently collects sensor data and controls environmental parameters for optimal Lai Chau ginseng growth. The DHT22 sensor measures humidity (0-100% RH) and temperature (-40 to +80°C) with high accuracy (2-5% RH and ±0.5°C, respectively). It operates on 3-5V with a maximum current of 2.5mA during data transmission and provides digital output at 0.5Hz. The DS3231 real-time clock module ensures precise timekeeping, maintaining accurate time within ±0.5 seconds daily. It includes a temperature sensor with ±3°C accuracy and supports I2C communication, operating on 3.3 - 5.5V. The BH1750 Digital Light Sensor measures light intensity in lux with an internal ADC and provides readings via I2C communication. It operates on a 2.4 - 3.6V power supply, with a 1 - 65535 lux range and ±20% accuracy. This sensor is essential for monitoring light intensity to optimize photosynthesis and growth conditions for Lai Chau ginseng. Additionally, the relay module features three terminals, including NC (Normally Closed), NO (Normally Open), and COM (Common), which are isolated from the main circuit. In its default state, NC is connected to COM; when activated, COM switches to NO. It operates on DC 5V, with each relay consuming ~80mA, and can handle a maximum switching voltage of AC 250V ~ 10A or DC 30V ~ 10A. It includes an indicator light and selectable signal trigger via jumper. Measuring 5.0 cm × 2.6 cm × 1.9 cm and weighing 17 g, this module controls devices like LED lights and the water pump. The LCD 1602 display is widely used in microcontroller applications due to its ability to display diverse characters, ease of integration, low system resource consumption, and affordability. Combined with an I2C module, it simplifies interfacing by requiring only 4 pins. The LCD 1602 features a 2-line display with 16 characters per line, a blue backlight, a wide viewing angle, and high contrast. It operates at 5V DC, integrates an HD44780 controller, and has module dimensions of 80 mm × 35 mm × 9 mm, with a 64.5 mm × 16 mm display area. Finally, the RS385 water pump operates at 12 - 24V, with a water lifting capacity of up to 3 meters and a flow rate of 2 liters per minute. It can handle water temperatures up to 80°C, making it suitable for applications requiring efficient water movement.

Constructing a growth chamber using components such as the ESP32 microcontroller, DHT22 sensor, DS3231 real-time clock module, BH1750 light intensity sensor, LED LCD 1602 display, relay module, RS385 water pump, and LED grow lights is an economically viable option due to the affordability of each component. The ESP32 microcontroller offers robust processing capabilities and wireless connectivity at a fraction of the cost of more complex systems, ranging from 5 - 10 US Dollars. The DHT22 sensor provides reliable temperature and humidity readings without significant expense (1 - 2 US Dollars), while the DS3231 clock module ensures accurate timekeeping at a low cost (1 - 2 US Dollars). The BH1750 sensor, essential for monitoring light intensity, is budget-friendly yet effective (2 - 3 US Dollars). The LED LCD 1602 provides clear displays at a minimal cost (1 - 2 US Dollars), and the relay module facilitates automated control of environmental conditions economically (less than 1 US Dollars). The RS385 water pump allows precise irrigation control (3 - 4 US Dollars), and the LED grow lights (5 - 10 Dollars), known for their energy efficiency and long lifespan, offer an inexpensive solution for optimal plant growth. Together, these components form a cost-effective system that can be assembled with minimal investment, making it accessible for small-scale and educational applications.

To describe the concept of a growth chamber, central to the system is the ESP32-WROOM-32D microcontroller, which coordinates data collection and control operations. This powerful module supports 802.11 b/g/n/e/i Wi-Fi and Bluetooth BR/EDR v4.2 and BLE, ensuring strong wireless communication and remote monitoring capabilities. The ESP32's extensive peripheral support, including ADC, DAC, touch sensors, and multiple communication interfaces, makes it ideal for integrating various sensors and actuators in the growth chamber. We incorporated the DHT22 sensor to measure temperature and humidity for precise environmental monitoring, operating within a range of -40 - +80°C and 0 - 100% RH, respectively. This sensor's digital output minimizes environmental interference, providing reliable data for optimal growth conditions. The DS3231 real-time clock module ensures accurate timekeeping for scheduling light cycles and irrigation, with its high-precision crystal oscillator maintaining accuracy even during power outages. Light intensity is monitored using the BH1750 sensor, which provides direct lux readings over a range of 1 - 65535 lux, crucial for optimizing photosynthesis. The LED LCD 1602 display, combined with an I2C module, offers a user-friendly interface for real-time monitoring of environmental parameters, displaying data on a 2-line, 16-character screen with a blue backlight. The growth chamber's control systems include a relay module with NC, NO, and COM terminals, capable of switching up to AC 250V ~ 10A or DC 30V ~ 10A, used to manage devices like LED grow lights and the RS385 water pump. This water pump, operating at 12 - 24V with a flow rate of 2 liters per minute and a maximum water temperature of 80°C, ensures precise irrigation. Together, these components form an integrated, cost-effective IoT-based growth chamber that maintains optimal conditions for cultivating Lai Chau ginseng. The system's real-time monitoring and control capabilities facilitate precise environmental management, supporting the healthy growth and development of the ginseng plants.

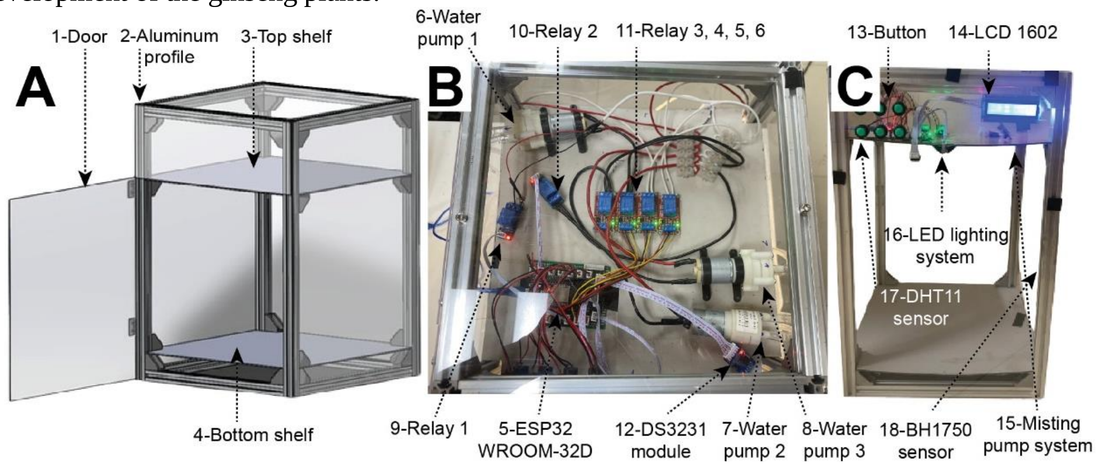

Figure 1. *Concept of a low-cost growth chamber for the growth and development of Lai Chau ginseng in Hanoi. (A) A physical structure of the growth chamber, (B) The internal wiring and key components that drive the growth chamber, (C) The control interface and additional sensors installed in the growth chamber.*

Recently, the growth and development of American ginseng (*P. quinquefolius*) under controlled growth chamber conditions were explored, focusing on adaptive differentiation to temperature [16]. By reciprocally transplanting ginseng populations from different elevations into growth chambers with varying temperature treatments, the study assessed fitness-related traits [16]. Results showed genetic differentiation and complex responses to temperature, with some traits not conforming to the expected 'home temperature' advantage [16]. Previously, these easy-to-use microcontrollers and inexpensive sensors have been utilized to construct a highly customizable growth chamber optimized for growing medical plants [17], [18].

3.2. Development of a mobile application for monitoring environmental parameters

Developing a mobile application for monitoring environmental parameters in the growth chamber is crucial for real-time data access and management [19]. This app would interface with the IoT-based sensors and controllers within the chamber, allowing users to remotely monitor key metrics such as temperature, humidity, light intensity, and soil moisture [19].

In this study, we developed a mobile application using Flutter (a UI toolkit by Google) to examine the growth chamber's environmental parameters. Particularly, this application can integrate seamlessly with the IoT sensors and microcontrollers in the growth chamber, providing real-time data on temperature, humidity, and soil moisture. The cross-platform capability of Flutter ensures that the application is accessible on Android and iOS devices. As a result, the application provides a real-time display of data from sensors like the DHT22 and BH1750, which measure temperature, humidity, and light intensity (Figure 2). This data is visually presented on the user interface, ensuring users can easily monitor environmental conditions. The intuitive layout uses Flutter's basic widgets, such as Scaffold, AppBar, Text, Image, and Container, to create a user-friendly experience. Next, the application includes remote control capabilities, allowing users to manage devices like the water pump and LED lights from their mobile devices. This feature enhances convenience and enables precise adjustments to maintain optimal growing conditions for Lai Chau ginseng. Users can access these controls through a well-organized interface that divides functionalities into distinct sections for ease of use (Figure 3). The third key feature is real-time notifications, which alert users to significant changes in environmental parameters or when device adjustments are needed. This proactive approach ensures that any issues can be promptly addressed, minimizing the risk of adverse plant growth conditions. Notifications are seamlessly integrated with the Firebase Realtime Database, which stores sensor data in JSON format and synchronizes it continuously between the growth chamber and the mobile application.

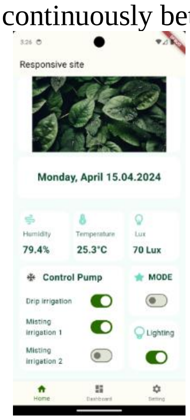

Figure 2. *A screenshot of a mobile application interface designed for monitoring and controlling a growth chamber. The interface provides real-time environmental data, including humidity, temperature, and light intensity, as displayed in the dashboard.*

Figure 3. *A low-cost IoT-based growth chamber designed for the adaptive differentiation of Lai Chau ginseng. The system includes a laptop (left) that displays data from the plant's environment. The growth chamber (right) houses a plant in a controlled environment.*

The application interface is divided into three main sections for comprehensive functionality. The Home page displays current environmental parameters and basic control options, while the Dashboard section visualizes measurement data through charts, allowing users to track trends and make informed decisions. The Settings page lets users configure system parameters, such as operation times and frequencies for various devices, providing full control over the growth chamber environment. Flutter's hot reload feature significantly speeds up development by allowing developers to see changes in the code instantly without recompiling the entire application. This efficiency, combined with the robust functionality of the application, ensures a smooth and effective tool for managing the growth chamber and optimizing conditions for ginseng cultivation.

3.3. Evaluation of the plant health of Lai Chau ginseng under the growth chamber conditions

To evaluate the plant health of Lai Chau ginseng individuals, several agronomical traits related to above-ground organs of plants, including plant height, leaf area, ChlF and Chl content. Figure 4 indicated that the treatment conditions (cultivation under the growth chamber condition) promoted better growth and higher Chl content in Lai Chau ginseng plants compared to the control.

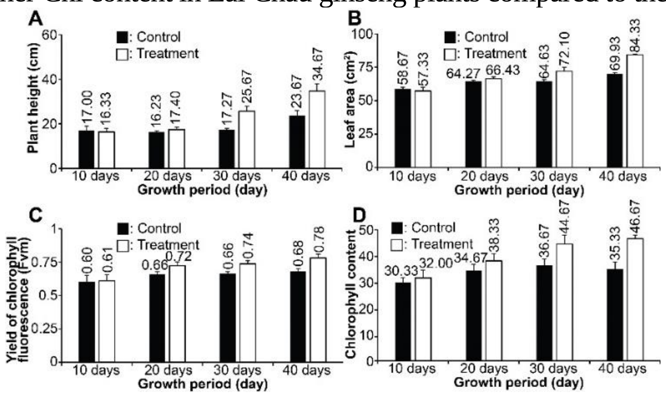

Figure 4. *Evaluation of the agronomical traits, including (A) plant height, (B) leaf area, (C) ChlF and (D) Chl content of Lai Chau ginseng plants under the growth chamber conditions*

Particularly, plant height data showed that while initial growth (10 and 20 days) was similar in both conditions, significant differences emerged at 30 and 40 days, with the treatment group reaching heights of 25.67 cm and 34.67 cm compared to the control group's 17.27 cm and 23.67 cm, respectively. Leaf area measurements revealed a steady increase in both groups, but the treatment group consistently had larger leaf areas, reaching 84.33 cm^2 by 40 days compared to the control group's 69.93 cm^2. Next, the ChlF remained relatively stable across both groups, with slight improvements observed in the treatment group. By 40 days, the treatment group reached a yield of 0.78 compared to the control group's 0.68, indicating better photosynthetic efficiency under treatment conditions. Finally, the Chl content data highlighted a clear advantage for the treatment group, which consistently showed higher chlorophyll levels. At 40 days, the treatment group had a Chl content of 46.67 compared to the control group's 35.33, suggesting enhanced photosynthetic capability under the treatment conditions. Overall, the treatments significantly improved plant height, leaf area, ChlF, and Chl content, demonstrating that the growth chamber's controlled environment positively impacted the growth and development of Lai Chau ginseng plants.

4. Conclusions

The study successfully established a low-cost IoT-based growth chamber for Lai Chau ginseng using various affordable sensors and modules, including an ESP32 microcontroller, DHT22 for temperature and humidity, DS3231 for timekeeping, BH1750 for light intensity, and RS385 for irrigation. A Flutter-based mobile app enables real-time monitoring and remote control of environmental parameters. Evaluations showed significant improvements in plant height, leaf area, chlorophyll fluorescence, and chlorophyll content under treatment conditions, demonstrating the growth chamber's effectiveness in promoting ginseng growth. Future work should optimize the IoT-based growth chamber by incorporating more advanced sensors and automation technologies to further enhance control over environmental parameters. Additionally, expanding the mobile application to include predictive analytics and machine learning capabilities could provide insights into optimal growth conditions and early detection of plant stress.

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