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Evaluating plant growth performance in a greenhouse hydroponic salad system using the internet of things

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ABSTRACT

Hydroponic salad cultivation is becoming increasingly popular. However, a common challenge is the lack of time to maintain hydroponic vegetables due to other responsibilities. This study presents a hydroponic system based on the internet of things (IoT) technique, designed to save time by enabling remote control through a mobile application connected to a NodeMCU microcontroller. Various sensors are integrated with the NodeMCU for real-time monitoring and automation. The study also explores the use of RGB LEDs, which significantly accelerated plant growth and reduced cultivation time. A comparative experimental design was employed to evaluate the growth rate of green oak salad vegetables under two different greenhouse systems. The primary factor compared was the greenhouse system type, with plant growth rate as the outcome variable. Each treatment was replicated 10 times. F-tests were used to statistically determine significant differences in growth rates between the two systems across measured intervals. Results showed that the automated greenhouse system produced the highest leaf width and plant weight values. The use of RGB LEDs reduced the cultivation period from 45 days to 30 days, enabling more planting cycles and ultimately increasing overall yield.

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1. INTRODUCTION

Recently, growing salad vegetables using a hydroponic system with the dynamic root floating technique (DRFT)—which circulates water containing nutrient solution through PVC pipes—has become increasingly popular, as nutrient solutions are easy to control. However, this method requires constant checking of pH levels, and the addition of nutrient solutions A and B must be adjusted appropriately for each type of salad vegetable, as this has a significant effect on plant growth. Since each type of vegetable has different nutrient requirements, temperature, humidity, air supply, and the amount of nutrient solution must be carefully controlled by measuring pH, or acidity/alkalinity. Normally, farmers must use equipment to measure pH every day until harvest. This process consumes a lot of time, and mistakes or discontinuities in measurement can lead to plant damage and production losses. Therefore, if a system can assist farmers by automatically controlling greenhouse parameters, it can help improve production quality. In terms of smart farming systems, the goal is for various processes to work automatically, reduce production costs, and minimize the use of manual labor [1]–[3].

Under these specific challenges, an automatic greenhouse control system was designed and developed using internet of things (IoT) technology [4], [5]. This system integrates watering, pH, temperature, humidity, and light control to improve production quality and shorten the planting period. The system was tested and evaluated, with results showing its effectiveness. Nguyen *et al.* [6] have designed and developed an automatic tracking system for hydroponic farming using IoT techniques. This system allows real-time collection of sensor data. IoT gateways and virtual servers have been developed to send the collected data to the cloud, enabling users to monitor all sensor readings related to the hydroponic solution and environment, as well as control farming equipment through a web interface. We tested and evaluated the nutrient film technique (NFT) hydroponic system during lettuce growth for 30 days. The experimental results showed that the proposed system demonstrated high reliability. The server was used to collect all the sensor data, which can be analyzed to study plant growth during cultivation in relation to environmental parameters.

Bakhtar *et al.* [7] introduced an indoor hydroponic planting system where plant roots are exposed to a mixture of minerals and water instead of soil and do not require sunlight, making the system independent of weather conditions. The system uses a microcontroller to collect and control data, including water level, temperature, and humidity, via Wi-Fi. Leveraging IoT technology, the real-time status of plant growth can be monitored remotely by authorized users. Kanhekar *et al.* [8] proposed a soil-less cultivation system using hydroponics, where mineral nutrients are supplied and parameters such as pH, temperature, and humidity are monitored through the Blynk app. This IoT-based system allows both monitoring and control of nutrient flow for hydroponic farming. The system is managed via an ESP8266 MCU node connected to the Blynk application. Additionally, Mapari *et al.* [9] developed a hydroponic farming system that reduces labor by automating the watering process. The novelty of this research is the automation of irrigation and the concept of vertical hydroponic cultivation using IoT. The system can display all important parameters in the application and notify users of abnormal conditions via email, such as pH, total dissolved solids (TDS), temperature, and humidity. Rao *et al.* [10] developed hydroponic systems to measure climate and nutrient levels using an automated computer control system. IoT-based system integration includes multiple sensors, such as water flow, water level, pH meter, electrical conductivity (EC), humidity sensor, and lux meter. Guzmán *et al.* [11], have proposed smart agriculture solutions using the LoRa microcontroller, an advanced IoT technology, providing low-power and low-cost remote communication. The system can communicate between nodes using both wireless networks and radio frequency signals, reporting temperature and humidity data across a wide area. Thus, the goal of this study is to develop and implement an IoT-based system for monitoring the growth of green oak salad, and to compare its development in an IoT-automated closed greenhouse versus a conventional one

2. METHOD

An automatic closed hydroponic salad vegetable cultivation system was investigated to solve the problems and meet the needs of farmers, including the design of structures and control systems. The experimental design and operation method were carried out for an automatic closed hydroponic salad vegetable growing system.

2.1. Structure and components of the control system

The intelligent hydroponic vegetable growing control system consists of structures and components connecting various sensor devices to the NodeMCU board (ESP8266). The NodeMCU board (ESP8266), which is similar to an Arduino board, is programmed to control operations according to commands. It was developed to control the turning on and off of water pumps, nutrient solutions A and B, and spraying water to reduce the temperature in the greenhouse [12], [13]. Data is stored on Google Sheets and displayed numerically through the Blynk application. Parameters such as temperature, nutrient solution levels, pH, artificial light from RGB bulbs (to accelerate vegetable growth), and humidity are measured using the C programming language. The results can be displayed on a smartphone, as shown in Figure 1.

The temperature device (DHT11) shown in Figure 2(a) illustrates the working flowchart of the temperature measurement system. From the diagram, when the temperature and humidity sensors take measurements, if the temperature is greater than 37.0 °C and the humidity is lower than 80%, the fog-spraying motor will turn on. The updated data are sent to the ESP8266 board, stored in Google Sheets, and displayed through the Blynk application. The complete procedure is shown in Figure 2.

The solution measuring device (pH sensor) shown in Figure 2(b) illustrates the working flowchart of the solution measuring system. When the sensor measures the pH value of the solution, if the pH value is less than 5.5 or greater than 6.0, the nitric acid motor will turn on to mix with fertilizer solutions A and B, after which the pH is checked again. If the pH value is within the specified range, the data are sent to the ESP8266 board, recorded in Google Sheets, and displayed numerically through the Blynk application. The RGB lighting system, shown in Figure 2(c), uses a relay switch to turn the RGB light bulbs on and off in order to enhance plant growth and reduce the overall planting period. The structural equipment consists of the NodeMCU control board (ESP8266), lighting sensor (LDR photoresistor module), pH sensor, temperature and humidity sensors (DHT11), RGB light bulbs, water pump, mist spray set, solenoid valve, and notebook computer. A specification comparison between the conventional greenhouse and the automatic closed greenhouse is provided in Table 1.

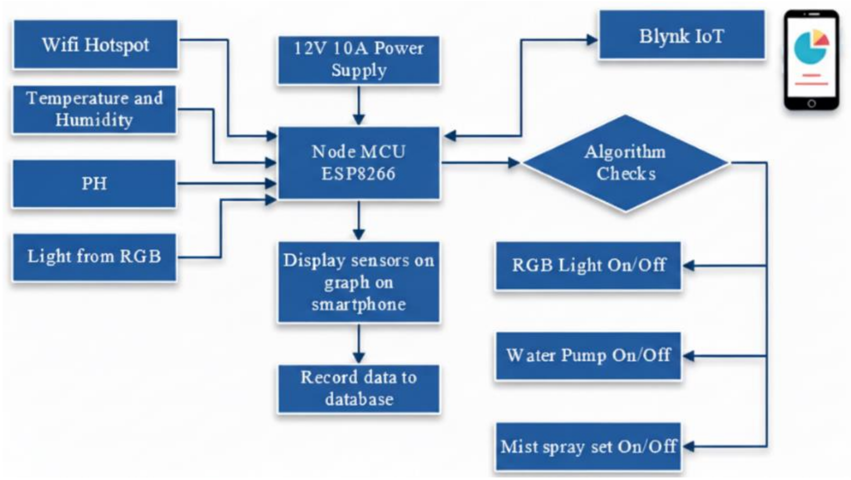
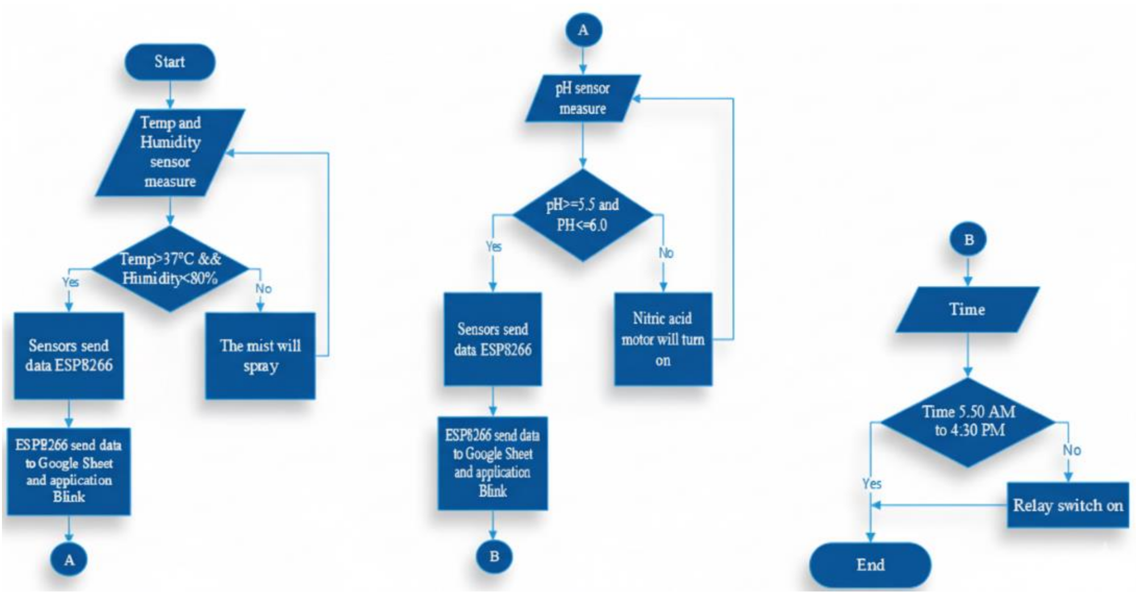


Figure 1. Diagram of methodology

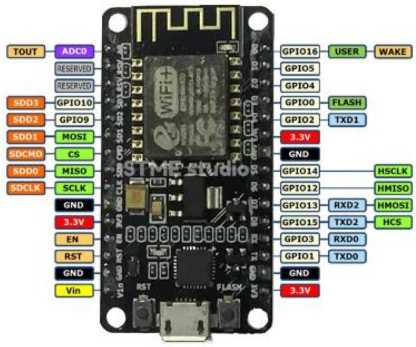
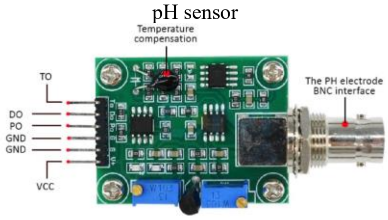


(a) (b) (c)

Figure 2. Schematic of temperature sensor, pH sensor, and RGB light (a) temperature lamps device (DHT11), (b) acid-base (pH) measuring device, and (c) RGB light

The green oak salad seeds were planted in seedling trays for 20 days. The young green oak seedlings were then transplanted into hydroponic gullies using both the automated system and conventional methods in the same location. The automatic system was set up to control the environment with pH between 5.5 and 6.6, temperature not exceeding 37 °C, relative humidity not less than 80%, and RGB lighting to accelerate growth. In the conventional method, standard farming practices such as manual watering and fertilization were applied. Data was collected and stored in Google Sheets, analyzed through the ESP8266 board, and displayed via the Blynk application on a smartphone.

Table 1. Specification comparison of the equipment between conventional greenhouse and automatic closed greenhouse in used

Items	Conventional greenhouse Specification	Automatic closed greenhouse Specifications
Control board Node MCU (ESP 8266)  	No	Development Kit (board) and Firmware (Software on the board) that open source can be programmed, Wi-Fi module (ESP8266)
Lighting sensor (LDR Photoresistor Sensor Module)  	No	Voltage 3.3-5.0 V Current 15 mA
pH sensor  	No	0-14 pH output, Analog (0-1023), Voltage 5 V, Can be immersed in water at all times.
Temperature and humidity sensors (DHT 11 Sensors)  	No	Voltage 3-5 V Current 2.5 mA, Humidity 20%-80% Temperature 0-50 °C
RGB light bulb 	No	Voltage 12 V Wavelength (Red 620-625 nm); (Green 520-525 nm); (Blue 465-470 nm)
Water pump 	No	Sonic AP2500 AC 220-240 V, 30-32 W, Q = 2,000 L/h, Head =2.0 m
Foggy spray set 	No	Pressure 6-7 bar, Voltage 12 V
Solenoid valve 	No	Operating power 12 V, Terminal operating temperature -20~+80 °C, operating pressure 0.2~8.0 kg.f/cm^2
Notebook computer	No	CPU Ryzen 7 4800H RAM 8 GB DDR 4 3200MHz SSD M.2 512 GB GPU RTX 3050

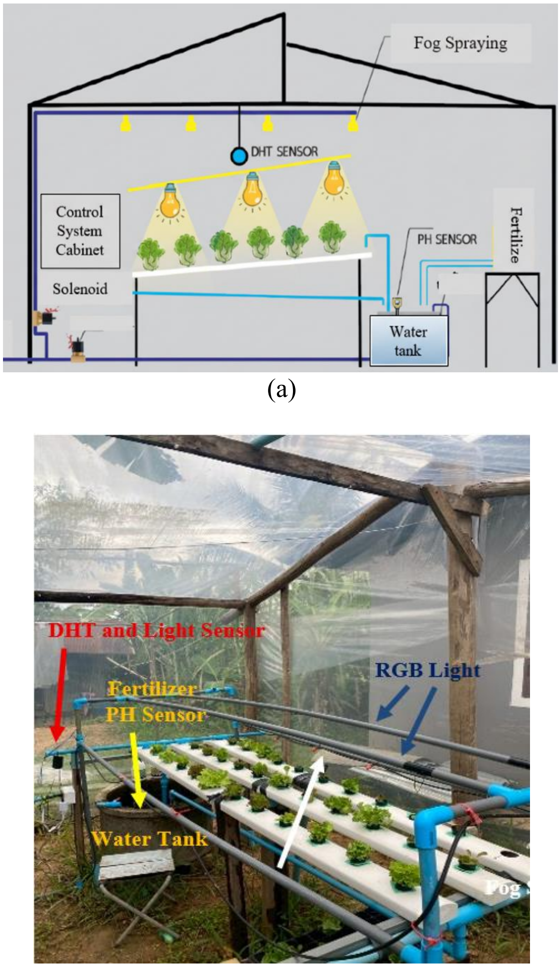
2.2. System working design

Recently, most modern indoor agricultural farms have implemented intelligent control systems to regulate and monitor optimal environmental conditions for plant growth, such as nutrient levels in water, humidity, and temperature [14]. The operation control system design uses inputs from various sensors, including a pH sensor, a humidity sensor, and a temperature sensor (DHT11) for environmental monitoring [15]. If erroneous data are detected—indicating the system is not functioning properly—the data are sent back to the microcontroller, and the system reprocesses the input before sending output commands. The output section is connected to the water pump, RGB lights, and fog sprayer, which receive input signals processed by the microcontroller. The main component is a pH sensor connected to the ESP8266, which is programmed to control various functions such as the water transport motor and the stirring motor for mixing fertilizer with water. After mixing, the soluble nutrients are released into the planting plots, and the results are displayed in Google Sheets and on the mobile application.

The structural design of the greenhouse is shown in Figure 3(a) and the equipment-installed greenhouse is shown in Figure 3(b). Equipment locations were tested and optimized during setup. Data from various sensors—temperature, humidity, pH, light status, and fog spraying status—are displayed on the system interface, as shown in Figure 4(a). The IoT system architecture as illustrated in Figure 4(b). Figure 5 shows the completed hydroponic greenhouse control box, which includes:

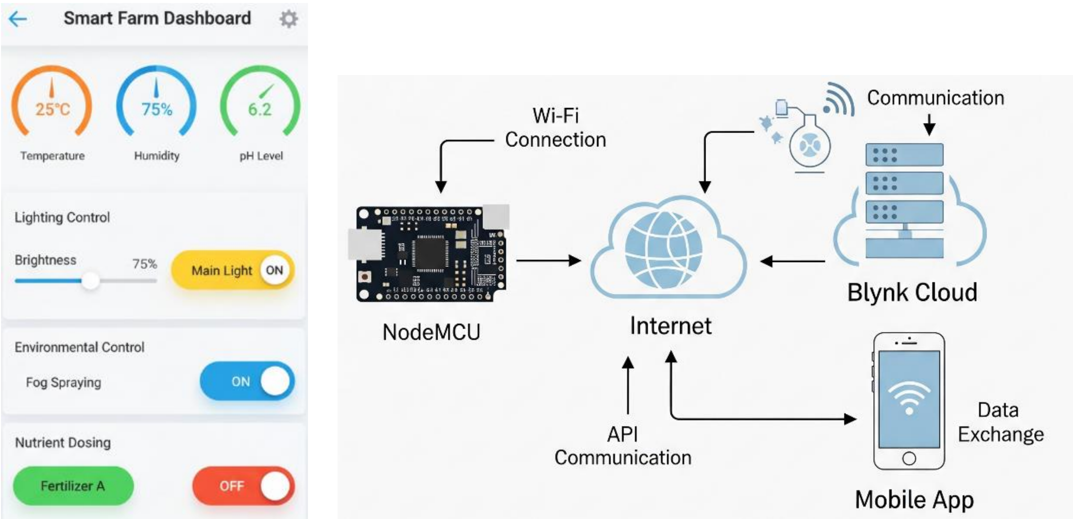
- ESP8266 board for controlling and receiving data from sensors and operating relay switches
- Relay switches for controlling fog pumps, solution pumps, and RGB bulbs
- A 12 V power supply used for devices connected to the relay switch

The experiment involved temperature control, relative humidity control, water and fertilizer suitability testing (fertilizer A: calcium and nitrogen; fertilizer B: phosphorus, potassium, and magnesium), as well as lighting control to accelerate plant growth and improve plant health.



(b)

Figure 3. Example of (a) a greenhouse structural design and (b) the equipment-installed greenhouse



(a) (b)

Figure 4. System application page (a) dashboard and (b) IoT system architecture

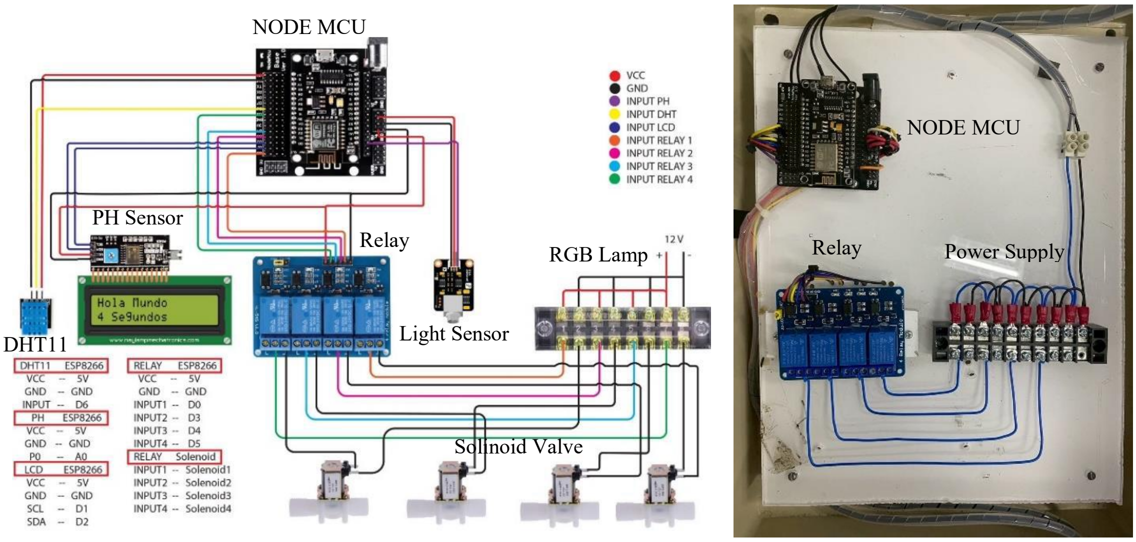


Figure 5. Connecting the hydroponic greenhouse control system

3. RESULTS AND DISCUSSION

Thailand is located in the tropical region of Southeast Asia, with an average annual temperature of approximately 27.88 °C. However, the temperature inside a greenhouse primarily depends on external parameters such as location, ambient temperature, solar radiation, and greenhouse design [16]. High humidity combined with temperatures above 25 °C can reduce yield, while high night temperatures and high humidity with low sunlight can cause excessive vegetative growth and low productivity [17]. To evaluate the performance of the two greenhouse systems, both inside and outside temperatures were monitored throughout the study. The results showed that the internal temperature of the conventional greenhouse ranged between 35 °C and 37.2 °C, whereas the automatic closed greenhouse maintained a lower range of 31.4 °C to 35.5 °C. Meanwhile, the outside temperature was observed to vary between 34.2 °C and 42.4 °C, as shown in Figure 6. The results of the relative humidity experiment in the greenhouse showed that the relative humidity in the conventional greenhouse was lower than 80%, which caused the internal temperature to rise above 37 °C, making it higher than that of the automatic closed greenhouse as shown in Figure 7.

The comparison of soluble values between the automatic and conventional systems is presented in Figure 8. The automatic system maintained stable pH values within the optimal range of 5.5–6.5, whereas the conventional system produced unsatisfactory results with fluctuating pH values. In the conventional system, soluble were added manually every 14 days. The lighting system is switched on at 06:00 p.m. and switched off at 06:00 a.m. via a relay switch (Figure 9) to accelerate plant growth, with monitoring conducted every 10 days as shown in Tables 2–4. Figure 9 illustrates the automatic closed greenhouse system. Figure 9(a) shows seedlings in trays, Figure 9(b) presents 20-day-old salad plants prior to transplanting, Figure 9(c) displays young seedlings inside the automatic greenhouse, and Figure 9(d) demonstrates the RGB lighting applied within the system.

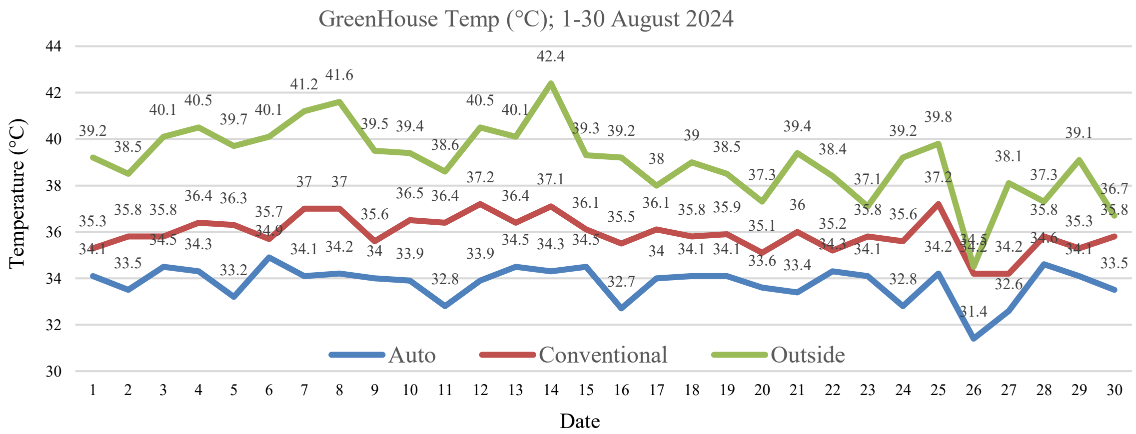


Figure 6. Results of the temperature experiment in the greenhouse (days 1-30)

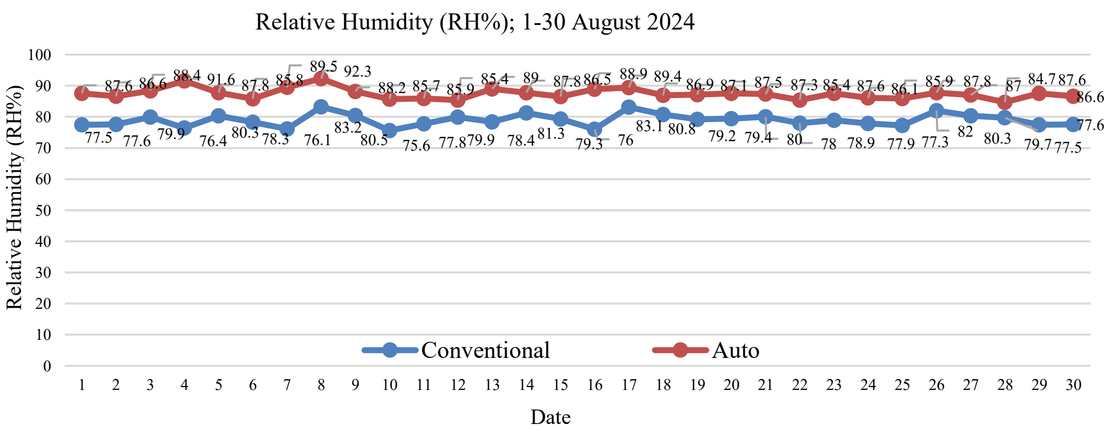


Figure 7. Graph showing the results of the humidity experiment in the greenhouse (days 1-30)

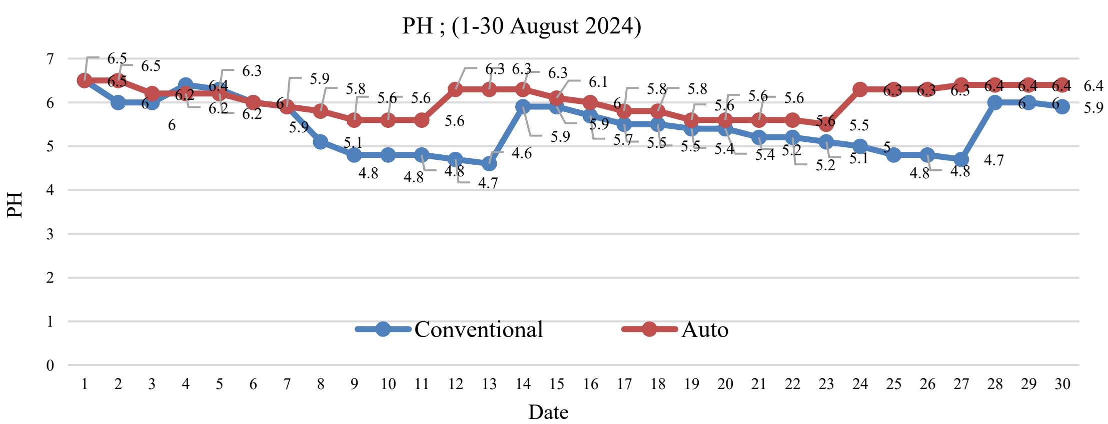
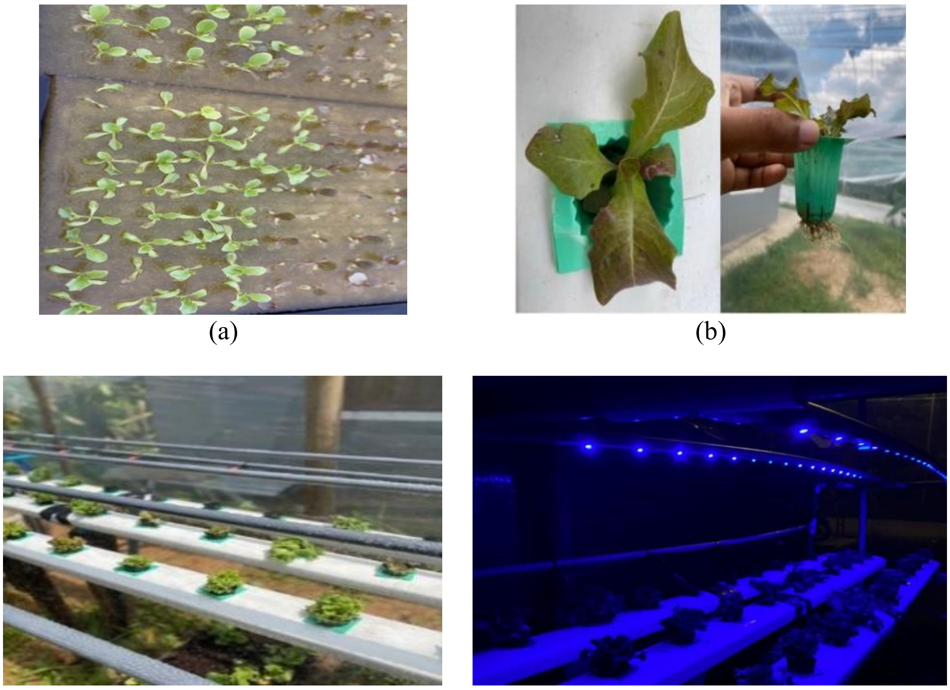


Figure 8. Graph showing the results of the experiment on soluble values in the greenhouse (days 1-30)



(a) (b) (c) (d)

Figure 9. Automatic closed greenhouse in operation (a) seedlings in tray, (b) 20 days salad before transplanting, (c) young seedlings salad in automatic greenhouse, and (d) RGB light used in automatic greenhouse

Table 2. Growth results of salad vegetables at 10 days (after transplanting)

Salad	Average			
Green Oak	Height (cm)	Max. Leaf Width (cm)	Max. Leaf Length (cm)	Weight (g)
Auto Greenhouse	7.54	7.16	7.64	52.5
Conventional Greenhouse	5.97	5.2	5.98	37
F-Test (P-value)	0.001	0.030	0.018	0.000
C.V.%	0.125	0.301	0.209	0.091

Table 3. Growth results of 20 days old salad vegetables (after transplanting)

Salad	Average			
Greenoak	Height (cm)	Max. Leaf Width (cm)	Max. Leaf Length (cm)	Weight (g)
Auto Greenhouse	7.98	13.44	12.26	76.7
Conventional Greenhouse	7.17	11.75	11.15	73
F-Test (P-value)	0.032	0.000	0.185	0.001
C.V.%	0.103	0.063	0.151	0.030

Table 4. Growth results of salad vegetables for 30 days (after transplanting)

Salad	Average			
Greenoak	Height (cm)	Max. Leaf Width (cm)	Max. Leaf Length (cm)	Weight (g)
Auto Greenhouse	19.26	14.05	13.09	119.28
Conventional Greenhouse	17.99	12.8	12.19	109.12
F-Test (P-value)	0.050	0.001	0.065	0.005
C.V.%	0.073	0.05	0.081	0.063

The results showed a growth comparison of the plants at 10 days after the first seedlings as shown in Table 2, Figures 10 and 11. The average growth rate of salad vegetables in the automatic system was 7.54 cm, while the conventional system measured 5.97 cm. The average leaf area (width×length) was 54.7 cm² in the automatic system compared with 31.09 cm² in the conventional system. Similarly, the average plant weight was 52.5 g in the automatic system and 37 g in the conventional system. Statistical analysis further confirmed that the average height of 10 plants grown under the automatic system (7.54 cm) was significantly greater than that of plants grown in the conventional system (5.97 cm) at $P = 0.05$. The mean leaf width in the conventional system was 5.2 cm, whereas the automatic system achieved 7.16 cm, a statistically significant difference (P = 0.05). The average length of the largest leaf was 5.98 cm in the conventional system compared with 7.64 cm in the automatic system, which was also significantly different at P = 0.05. Finally, the mean plant weight was 37 g in the conventional system and 52.5 g in the automatic system, showing a highly significant difference at P = 0.05.

Figure 10. Salad vegetable in conventional system at 10 days (after transplanting)

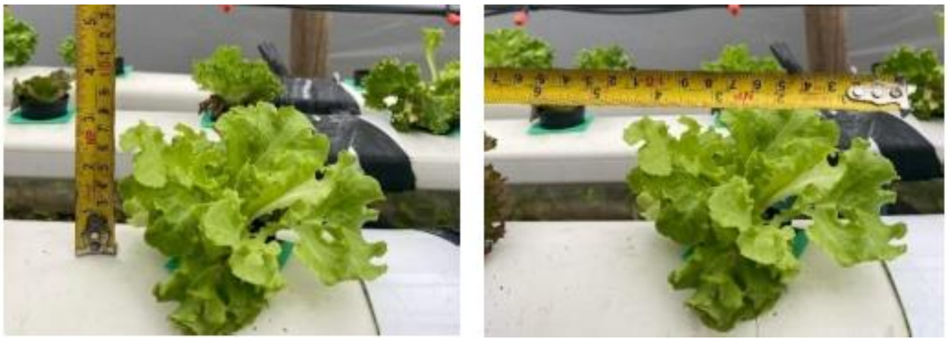


Figure 11. Salad vegetables in automatic system at 10 days (after transplanting)

The comparison growth at 20 days after planting is demonstrated in Table 3. The average growth rate of salad vegetables in the automatic system had a higher height value of 7.98 cm, whereas the conventional system recorded 7.17 cm. The average (width×length) value of the automatic system was 164.7 cm, while the conventional system measured 131.0 centimeters, and the growth weight in the automatic system was 76.7 g compared to 73 g in the conventional system. Furthermore, the analysis of the average height of the green oak salad vegetables after 20 days showed that the average height of 10 plants grown with the conventional system was 7.17 cm, while those grown with the automatic system reached 7.98 cm, which was statistically different at P = 0.05. The analysis of the mean width of the largest leaves in the conventional system was 11.75 cm, whereas in the automatic system it was 13.44 cm, a very statistically significant difference at P = 0.05. The analysis of the average length of the largest leaf in the conventional system was 11.15 centimeters, whereas in the automatic system it was 12.26 cm, which was not statistically different at P = 0.05. Finally, the analysis of the mean plant weight in the conventional system was 73 g, while in the automatic system it was 76.7 g, showing a highly significant difference at P = 0.05.

The comparisons of growth after 30 days at harvest time are shown in Table 4. It can be seen that the average height of salad vegetables in the automatic system was 19.26 cm, whereas the conventional system recorded 17.99 cm. The average (width × length) value of the automatic system was 419.61 cm, while the conventional system was 368.2 cm. The average plant weight in the automatic system was 119.28 g, whereas the conventional system produced an average weight of 102.12 g.

Furthermore, the practical performance was evaluated through variance analysis, as shown in Table 5. The results for the average height of green oak salad vegetables at 30 days after planting showed that the average height of 10 plants grown with the conventional method was 17.99 cm, while those grown with the automatic system reached 19.26 cm, which was not statistically different at P = 0.05. The mean width of the largest leaves in the conventional system was 12.8 cm, whereas in the automatic system it was 14.5 cm, showing a highly statistically significant difference at P = 0.05. The average length of the largest leaf in the conventional system was 12.19 cm, compared with 13.09 cm in the automatic system, which was not statistically significant at P = 0.05. The mean plant weight was 109.12 g in the conventional system, while it was 119.28 g in the automatic system, showing a very significant difference at P = 0.05. A comparison based on mean values using the DMRT method is presented in Table 5. From this analysis, it can be emphasized that the automatic greenhouse effectively promotes the growth of green oak salad vegetables under the tested conditions.

Table 5. Comparison between mean values of the growth rate

Harvest day	Result	Height (cm)	Max. Leaf Width (cm)	Max. Leaf Length (cm)	Weight (g)
10 days	Conventional greenhouse	5.97 ± 0.86^{a}	5.20 ± 0.79^{a}	5.98 ± 0.77^{a}	37.00 ± 4.83^{a}
	Auto greenhouse	7.54 ± 0.83^{b}	7.16 ± 2.5^{b}	7.64 ± 1.85^{b}	52.5 ± 3.12^{b}
20 days	Conventional greenhouse	7.17 ± 0.69^{a}	11.7 ± 0.81^{a}	11.14 ± 1.71^{a}	72.9 ± 2.29^{a}
	Auto greenhouse	7.98 ± 0.86^{b}	13.44 ± 0.77^{b}	12.14 ± 1.80^{a}	76.7 ± 2.14^{b}
30 days	Conventional greenhouse	17.99 ± 1.46^{a}	12.8 ± 0.54^{a}	12.19 ± 0.94^{a}	109.12 ± 4.13^{a}
	Auto greenhouse	19.26 ± 1.23^{b}	14.05 ± 0.79^{b}	13.09 ± 1.10^{b}	110.28 ± 9.27^{b}

Note: Means followed by the different superscript in the same column indicate significant difference between the mean values at P= 0.05.

Previous studies support these findings. Domingues *et al.* [18] compared lettuce growth under conventional soil cultivation and an automated hydroponic system. The research results indicate that the automated hydroponic system has a shorter harvesting period (reduced from 71 days to 64 days), helps reduce labor, and increases crop yield. According to research [19], low pH levels lead to a rapid reduction in hydraulic conductivity and surface water flow in seedling trays. Moreover, Cui-Ping *et al.* [20] reported that low pH reduces the photosynthesis rate, as plants inhibit CO_2 absorption, resulting in a decrease in the average number of leaves and plant height. In indoor agricultural systems, plants primarily absorb light within the blue (B, 400–500 nm) and red (R, 600–700 nm) regions of the spectrum, corresponding to the peak absorption of key photosynthetic pigments, chlorophyll (a) and chlorophyll (b) [21].

Previous studies have shown that an optimal ratio of red to blue light should be provided to plants. For lettuce (Lactuca sativa L.), a 3:1 red-to-blue ratio has been observed as the most effective for achieving high yield, quality, and efficient resource use [22]. In this study, red, green, blue (RGB) lights were used to stimulate growth and reduce the cultivation period. The RGB lights used had the following specifications: Red 620–625 nm, Green 520–525 nm, and Blue 465–470 nm. This indicates that LED light effectively stimulates leaf enlargement in green oak hydroponic salad vegetables. Folta and Childers [23] observed that red and blue light receptors are the main photoreceptors controlling plant photomorphogenesis, with blue light specifically stimulating leaf enlargement and regulating gene expression. Similarly, Sabzalian *et al.* [24] demonstrated that red-blue LED incubators produced plants with higher shoots, longer roots, and greater fresh weights. In addition, Watjanatepin [25] which was conducted in a lettuce plant factory using a hydroponic system with LED lighting as the light source, reported improved plant growth and yield.

4. CONCLUSION

The development of an automatic hydroponic greenhouse control system used the Node MCU ESP8266 board as the main processing unit, receiving data from a temperature and humidity sensor (DHT11) and a water solution sensor (pH sensor). When the temperature exceeds 37 °C or the humidity falls below 80%, the board triggers the solenoid valve to spray fog, reducing temperature inside the greenhouse. This maintains suitable humidity for optimal growth of green oak hydroponic salad vegetables. In contrast, the conventional greenhouse lacks a fog sprayer, resulting in suboptimal growth. When the water pH is outside the range of 5.5–6.0, the board activates the pump to adjust the solution in the combined water tank, keeping it within the specified range.

Typically, salad vegetables take 45 days to reach harvest. However, in this study, cultivation in the automatic greenhouse was completed in just 30 days. A comparison of 10 plants grown under automatic conditions and 10 under conventional conditions showed that, after 30 days, the average height in the automatic greenhouse was 19.26 cm, with a maximum plant weight of 135 g (7th plant) and a minimum of 110 g (5th plant), giving an average weight of 119.28 g. In the conventional system, the average height was 17.99 cm, the maximum weight was 113.9 g (7th plant), and the minimum weight was 100.9 g (3rd plant), with an average of 109.12 g. The difference in average weight between the two systems was 10.16 g, achieved without the use of chemicals.

These results reflect that the automatic greenhouse can maintain an optimal internal environment-controlling relative humidity, temperature, lighting, irrigation, and fertigation-which promotes better growth of green oak salad vegetables under specific conditions and reduces the cultivation period. The highest values for leaf width and plant weight were observed in the automatic greenhouse. Overall, the automatic greenhouse performed well in this experiment. However, future studies should focus on simplifying the structure for easier maintenance, improving platform usability, and reducing the cost to develop a commercially viable prototype for farmer use.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Wiyuda Phetjirachotkul		✓	✓			✓	✓	✓	✓					
Isara Chaopisit				✓	✓	✓		✓		✓	✓	✓	✓	
Kronsirinut Rothjanawan				✓	✓		✓			✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

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