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Enhancing Chinese Cabbage Production and Quality through IoT-Based Smart Farming in NFT-Hydroponics

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Abstract: The rising adoption of agricultural technologies such as the Internet of Things (IoT) or "smart farming" aims to boost crop production in terms of both quantity and quality. This study compares the benefits of a smart farm employing an IoT-based hydroponic system with those of a conventional hydroponic farm, using Chinese cabbage (*Brassica pekinensis* L.) as the experimental crop. Our primary objective was to automate environmental monitoring, achieving pH level and electrical conductivity (EC) maintenance through smartphone or computer interfaces for nutrient and acid–base solution adjustments. Additionally, we evaluated plant growth and crop quality, finding superior results with the smart hydroponic system. On average, there were substantial increases in various parameters, including total fresh weight (27.14%), total dry weight (48.90%), plant height (11.14%), stem diameter (32.89%), leaf area (94.30%), leaf width (32.36%), leaf length (38.12%), and chlorophyll content (22.73%). Nitrate accumulation in the edible parts of Chinese cabbage remained within safe limits for both systems, reflecting careful nutrient management. These findings highlight the potential of IoT-based technology in enhancing productivity and quality in hydroponic farming, marking a significant step towards revolutionizing traditional agricultural practices for more efficient crop production systems.

Keywords: comparative analysis; physiological responses; yield; nitrate accumulation; Chinese cabbage; hydroponics; smart farming

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1. Introduction

Smart farming, also referred to as precisely managed agriculture, utilizes advanced scientific and information technology to achieve effective conversion from input to output. Leveraging the most economical resources can lead to increased revenue, reduced costs, and a minimized environmental impact. This approach is convenient and swift, and it is anticipated to align with eco-friendly and sustainable farming practices. Farmers should adapt to stay in sync with technological advancements. Collaborating with researchers to explore technology and practically apply acquired knowledge to enhance farm productivity is crucial to addressing the escalating global food demands driven by population growth. Predicting and comprehending plant growth efficiency across diverse environments can elevate agricultural productivity [1].

Technology's application is on the rise across various sectors, including agriculture, where innovative technological advantages can significantly bolster both the quantity and quality of food production [2]. From technological advancements and smart agricultural automation to overseeing tasks like processing capabilities, agricultural scientists and cultivators are encouraged to adopt automated control systems for managing agricultural processes [3]. With the deployment of machines and sensors for farm management, data volume and scope escalate, resulting in data-centric and data-intensive farming approaches. The rapid development of the internet has propelled the emergence of "smart farming", marking the dawn of an era with extensive social and environmental influence [4].

In this context, Internet of Things (IoT) technology has emerged as a pivotal approach to revolutionizing farming. IoT technologies offer unparalleled capabilities in data collection and management, contingent upon factors like system design and network technology. The focus remains on fundamental, efficient traits and their application in agriculture. There are established effectiveness benchmarks and opinions regarding the suitability of smart farming, accompanied by challenges in its implementation [5].

Implementing IoT for monitoring indoor conditions can enhance crop growth in agriculture [6]. This encompasses not only house location but also augmented information processing triggered by real-time events and situational awareness. Rapid real-time configuration becomes essential in agile operations, particularly during sudden shifts in operating conditions or circumstances such as weather changes or epidemics [4].

Big data-related technologies play a pivotal role in creating sensor-based tools that measure data within work environments, capitalizing on integration with other external data sources like weather data, marketing information, or benchmarking with other farms. This is due to the challenge of storing and processing voluminous or intricate datasets within conventional data processing applications [7].

Urban development has posed several challenges, including the conversion of agricultural land into residential and industrial zones. Consequently, arable land availability in urban areas has diminished, while urban food requirements hinge on agricultural production to address the dwindling arable land issue. Hydroponics, a well-known cultivation method, has gained prominence among modern practices. Hydroponics involves cultivating plants in a nutrient solution environment [8].

Soilless cultivation through hydroponics has demonstrated accelerated growth rates and enhanced yields in comparison to traditional cultivation within the same environmental conditions. Furthermore, hydroponic systems exhibit reduced water consumption, the potential for nutrient solution recycling, and lowered susceptibility to soil-borne diseases [9]. Among the nutrient solutions utilized in hydroponics, the nutrient film technique (NFT) is prominent, involving the intermittent flow of the nutrient solution through plant troughs [10]. This process ensures the conveyance of water, nutrient solution, and oxygen to the plant [11], subsequently reaching the root region, where the quality of the nutrient solution plays a pivotal role in determining the effectiveness of soilless cultivation [12].

Chinese cabbage, scientifically known as *Brassica pekinensis* L., is a highly nutritious vegetable recognized for its abundant content of folic acid, a vital nutrient associated with blood health, and essential vitamins A, B, and calcium. It also boasts vitamin C and a range of essential minerals, including sodium, potassium, magnesium, and calcium, contributing to its nutritional profile [13]. Cabbage is extensively consumed as a dietary staple, with individuals consuming as much as 500 g day^{-1} on average in Brazil [14]. Furthermore, Chinese cabbage has gained popularity as a suitable and feasible crop for cultivation without soil, making it a preferred choice for methods such as hydroponics [15].

Thus, this study aimed to compare the hydroponic cultivation of Chinese cabbage utilizing IoT technology for cultivation management with the conventional hydroponic cultivation method, which relies on manual labor and measurement devices. The research objectives were as follows: (1) design a prototype smart agricultural system for hydroponic plant growth; (2) validate and deploy the prototype in a real-world setting; and (3) gather data on variables influencing the growth of the specific crop category, subsequently analyzing these values to contrast with conventional cultivation measurement techniques, with the intention of advancing precision farming practices.

2. Materials and Methods

2.1. System Design

The design of an automated hydroponic greenhouse system for use in a closed-system environment involves a control system for operation commands, device control, sensor data reading, and data collection of plant growth images. This is achieved through Machine Learning on the Amazon Web Services (AWS) Cloud, as illustrated in Figure 1. The operation is divided into three main parts: (1) Monitoring: This component displays the real-time status and operation of devices, enabling controllers to verify whether the system is functioning normally according to commands; (2) Semi-Automatic Control: This function allows users to control the operation of various devices manually, while the automated system receives input from sensors and processes data to display graphs and numerical results; and (3) Settings: Users have the ability to set initial profiles for devices. This involves receiving input from a keypad to configure starting or ending settings for the devices.

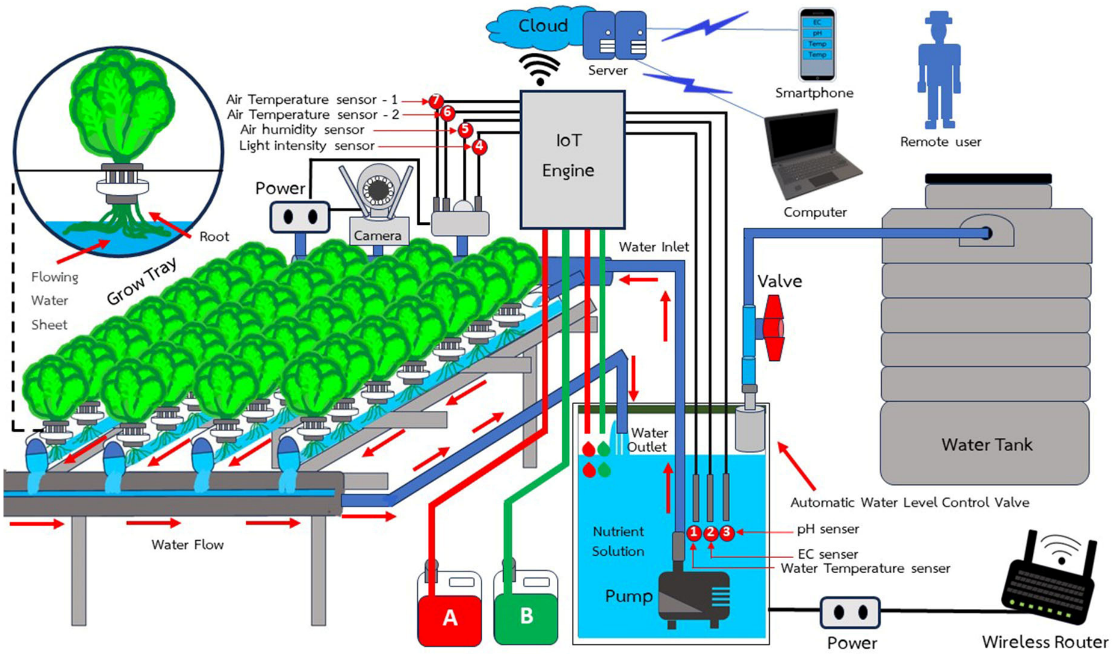


Figure 1. A diagram of a prototype of an intelligent farm system for NFT-hydroponic plant cultivation, controlled using IoT technology. Sensors: The system uses various sensors to monitor the condition of the plants and the growing environment. These include a pH sensor (1), an EC sensor (2), a water temperature sensor (3), a light intensity sensor (4), an air humidity sensor (5), an air temperature sensor (6,7), and a camera. Control unit: The system uses a computer to process the data from the sensors and control the actuators based on the readings. Actuators: The system uses various actuators to control the growing environment and nutrient delivery. These include a water inlet valve, an automatic water level control valve, a water pump, and a nutrient solution pump. Cloud: The system can be connected to the cloud, which allows remote monitoring and control of the system. Remote user: The system can be monitored and controlled by a remote user through a smartphone or computer. Nutrient Solution (A and B): The hydroponic system uses a two-part nutrient solution that provides plants with the nutrients they need to grow.

2.1.1. Hardware

In the hardware design, the system employs microcontrollers (Arduino Uno) as data aggregators from various sensors: an EC sensor, a pH sensor, and a temperature and humidity sensor. Sensor data are transmitted to the control unit using a wireless communication protocol (Bluetooth Low Energy). All data transmission is encrypted to ensure security. These data are then transmitted to a signal receiver board, which serves as a gateway in the IoT network. The gateway connects to an internal server, enabling the conversion of analog data signals into a format suitable for web interfaces and mobile devices. A real-time clock (RTC) is utilized for time tracking. When a command is issued to release a nutrient solution into the system, the command is sent to the signal receiver unit. This unit then forwards the command to the control board, which is connected to a 4-relay module (EC up, EC down, pH up, and pH down). This relay module commands the operation of motors, facilitating the injection of nutrient solutions into the system (Figure 2). The system consists of seven sensors, including an electrical conductivity (EC) sensor (DFRobot, Shanghai, China), a pH sensor (DFRobot, Shanghai, China), two air temperature sensors (Aosong Electronics Co., Ltd., Guangzhou, China), a water temperature sensor (Analog Devices, Wilmington, MA, USA), an air humidity sensor (Aosong Electronics Co., Ltd., Guangzhou, China), and a light intensity sensor (ROHM Semiconductor, Kyoto, Japan). The types of sensors, models, and technical specifications used in this study are shown in Table 1.

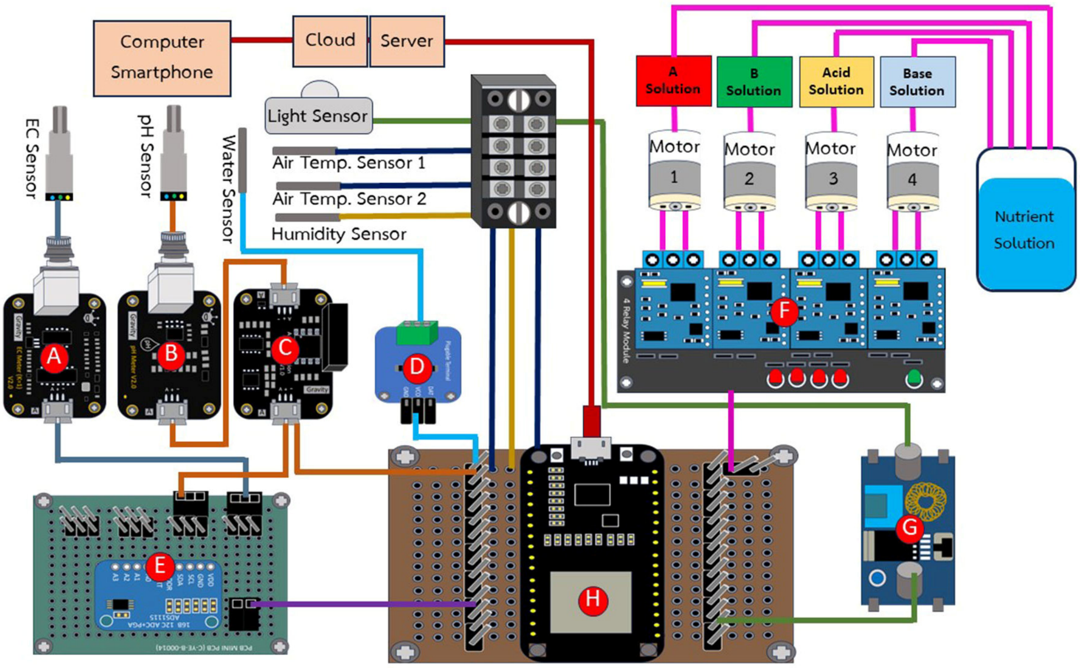


Figure 2. The hardware design of a hydroponics system monitoring and control system. Microcontroller Units (MCUs) (A, B, C, D, and G): These small computers receive sensor signals and convert them into digital data. Signal Boards (E, H): Board (E): receives digital data from MCUs and transmits it to the server. Board (H): Acts as the IoT gateway, receiving data directly from light, air temperature, and humidity sensors and then transmitting it all to the server. Control Board (F): Receives commands from the server and controls the motor operation. Relay Modules (1, 2, 3, and 4): These modules act as switches, receiving control signals from the control board and turning the motor on or off.

Table 1. Types of sensors and model/technical specifications used in this study.

Kinds of Sensor	Types of Sensor	Model/Technical Specifications
pH sensor	Analog pH meter	Model: DFRobot's Gravity V2 Signal Conversion Board (Transmitter) V2 Supply Voltage: 3.3~5.5 V, Output Voltage: 0~3.0 V, Probe Connector: BNC, Signal Connector: PH2.0–3 P, Measurement Accuracy: ±0.1@25 °C, Dimension: 42 mm × 32 mm/1.66 × 1.26 in pH Probe Probe Type: Laboratory Grade, Detection Range: 0~14, Temperature Range: 5~60 °C, Zero Point: 7 ± 0.5, Response Time: <2 min, Internal Resistance: <250 MΩ, Probe Life: >0.5 year (depending on frequency of use), Cable Length: 100 cm [16]

Table 1. *Cont.*

Kinds of Sensor	Types of Sensor	Model/Technical Specifications
EC sensor	Analog electrical conductivity meter	Model: DFRobot's Gravity V2 (K = 1) Signal Conversion Board (Transmitter) V2 Supply Voltage: 3.0~5.0 V, Output Voltage: 0~3.4 V, Probe Connector: BNC, Signal Connector: PH2.0–3 Pin, Measurement Accuracy: ±5% F.S., Board size: 42 mm × 32 mm/1.65 in × 1.26 in Electrical Conductivity Probe Probe Type: Laboratory Grade, Cell Constant: 1.0, Support Detection Range: 0~20 ms/cm, Recommended Detection Range: 1~15 ms/cm, Temperature Range: 0~40 °C, Probe Life: >0.5 years (depending on the frequency of use), Cable Length: 100 cm [17]
Water temperature sensor	Digital temperature sensor	Model: FZ0144B/Waterproof Operating voltage: 3.0~5.5 V, ±0.5 °C Accuracy from −10 °C to +85 °C, Usable temperature range: −55 to 125 °C (−67 °F to +257 °F), 9 to 12 bit selectable resolution, Uses 1-Wire interface- requires only one digital pin for communication, Unique 64-bit ID burned into chip, Multiple sensors can share one pin, Temperature-limit alarm system, Query time is less than 750 ms, 3 wires interface: VCC, GND and DATA, Stainless steel tube 6 mm diameter by 35 mm (1.34″) long, Cable diameter: 4 mm (0.16″), Length: 90 cm (35.43″) [18]
Light intensity sensor	Digital light intensity detection	Model: BH1750FVI Original BH1750FVI chip using ROHM, Power supply: 3–5 V Data range 0–65,535, Sensor built 16bitAD converter, Direct digital output, omitting complex calculations, calibration is omitted, Does not distinguish between ambient light, Spectral characteristics close to visual sensitivity, Brightness can be a wide range of high-precision measurement lux, outer diameter 26 mm, large diameter 28.5 mm, high 26 MM (plus light ball), spectral sensitivity characteristics: peak sensitivity wavelength typical value: 560 nm, Light source dependence is weak: incandescent lamp, fluorescent lamp, halogen lamp, white LED, fluorescent lamp [19]
Air humidity sensor	Digital-output relative humidity sensor	Model: DHT22, Power supply: 3.3–6 V DC, Output signal: digital signal via single-bus, Sensing element: Polymer capacitor, Operating range: humidity 0–100%RH, Accuracy: humidity ±2%RH(Max ±5%RH), Resolution or sensitivity: humidity 0.1%RH, Repeatability: humidity ±1%RH, Humidity hysteresis: ±0.3%RH, Long-term Stability: ±0.5%RH/year, Sensing period: Average: 2 s, Interchangeability: fully interchangeable, Dimensions: 14 × 18 × 5.5 mm [20]
Air temperature sensors	Digital-output relative temperature sensor	Model: DHT22, Power supply: 3.3–6 V DC, Output signal: digital signal via single-bus, Sensing element: Polymer capacitor, Operating range: temperature −40~80 °C, Accuracy: temperature < ±0.5 °C, Resolution or sensitivity: temperature 0.1 °C, Repeatability: temperature ±0.2 °C, Humidity hysteresis: ±0.3%RH, Long-term Stability: ±0.5%RH/year, Sensing period: Average: 2 s, Interchangeability: fully interchangeable Dimensions: 14 × 18 × 5.5 mm [20]

2.1.2. Software

The ThingsBoard platform version 3.2.1 is used for controlling sensors and actuators, including nutrient solution pumps and pH control pumps. It enables remote monitoring, data visualization, and automatic system operation based on predefined parameters. The system is configured as an Internet of Things (IoT) network, allowing remote monitoring and control. It can automatically check and report on the server's status and perform a restart if necessary. The IoT network enables users to view received data and receive user commands. The Smart Hydroponic Board is designed to enable users to control motor activation and deactivation. The displayed values change with real-time updates reported every 5 s. Furthermore, the system can be controlled conveniently through mobile phones, enhancing user control. Users can also inspect parameters similarly to using a computer. Additionally, the system includes cameras for day and night monitoring to assess plant growth. It can also capture images of intruders and send alerts to phones, facilitating communication with farm workers through the camera system. In the event of unforeseen incidents such as power outages or electrical failures, which might lead to sensor malfunctions or electronic component failures affecting the system's operation, data will not be lost or halted. The software records data, allowing retrieval for analysis at a later time.

The operation control of the nutrient solution replenishment pump and the pH control pump is achieved through software communication with the devices over a Local Area Network (LAN) as follows: Automatic Operation Control: The program communicates with the devices to automatically turn the motors on or off for nutrient solution replenishment and pH adjustment. Users can set appropriate parameter ranges for these processes. Data Presentation Formats: The system provides two data presentation formats: numerical data and graphical representations, including line graphs and semi-circle charts. The control is divided into 3 levels for general vegetable cultivation: (1) Seedling Cultivation Phase (Small level): Age of seedlings is 0–14 days; (2) Middle Growth Phase (Middle level): Age of plants is 15–28 days; and (3) Maximum Growth Phase (High level): Age of plants is 29–42 days. Each level has an automatic control profile stored in the control box within the greenhouse. Before use, users need to configure the initial profiles for each level to be suitable for the specific stage of growth. This enables the system to memorize and execute operations based on the preset values. The variables are shown in Table 2.

Table 2. IoT system control variables.

Variable	Value	Meaning
Temperature	°C	Internal temperature within the greenhouse
Light	Lux	Light intensity within the greenhouse
Humidity	%	Air humidity within the greenhouse
Element A	On/Off	Nutrient solution element A
Element B	On/Off	Nutrient solution element B
pH	pH	pH level of the nutrient solution

2.2. IoT System Installation

The system employs secure login credentials for multi-user access, ensuring authorized personnel can only control and monitor the system.

The installation of the IoT system's control box (Smart Hydroponic Box) involves integrating the control circuit board with the farm's electrical system. The light sensor is positioned appropriately to measure light levels accurately. It is placed in a location near the plant area to closely resemble the light conditions during midday. For the installation of the humidity and air temperature sensors inside the greenhouse, careful placement is required. The humidity sensor and air temperature sensor are positioned in a suitable area, elevated from the ground, to prevent exposure to moisture from rain or water droplets. This positioning also helps safeguard against potential damage from rodents or ants that might interfere with the wiring or sensors.

The installation process for the pH sensor involves calibration using buffer solutions prepared from pH Buffer Powder, which include solutions with pH 4.01 (acidic) and pH 6.86 (basic) states. Once calibrated, the pH sensor is installed in the nutrient solution tank. Similarly, for the EC (Electrical Conductivity) sensor, calibration is necessary using solutions that provide EC values of 1.413 mS/cm and 12.88 mS/cm. After calibration, the EC sensor is placed in the nutrient solution tank along with the water temperature sensor. Furthermore, the Periha Aqua Heater HB-100 is installed to maintain the water temperature at an appropriate range of 24.3–28.2 °C within the nutrient solution tank, as recommended by de Lira et al. [21]. After the installation is completed, the system is activated to establish connections with the internet network and the smartphone app. Users, with multi-user access using secure login credentials, can then remotely control the system for added security. Additionally, an outdoor security camera (imilab EC3 Outdoor Security Camera; Power Input 12 V:1 A) is installed to capture the growth progress of the plants. Placed strategically, it covers the entire cultivation area. The camera is linked to the Mi Home app on smartphones, allowing users to configure and control the camera settings. This feature supports multiple users, and the app sends real-time motion alerts when an intrusion is detected. It also enables continuous data storage of images and videos throughout the cultivation period, facilitating retrospective analysis of the plant growth process.

2.3. Preparing a Nutrient Solution

We prepared concentrated stock solutions for nutrient elements A and B by mixing the components according to the pre-determined formula for each solution. The solutions are prepared separately to ensure they are well-mixed. The following formula outlines the preparation of a 50-L nutrient solution with a concentration of 100 times, as shown in Table 3. We divided the solution into six 6-L containers for subsequent use in the cultivation system. These formulas outline the specific quantities of each nutrient element to be added per 50 L of concentrated nutrient solution for both A and B solutions. These nutrient solutions will be further diluted and added to the hydroponic cultivation system.

Table 3. Nutrient solution components in concentrated nutrient solutions A and B.

Nutrient Elements	Amount (g 50 L^{-1})
A Solution	
$CaNO_3$ (15.5-0-0 + 26.5CaO)	5500
Fe-EDTA 13.0%	200
Fe-DTPA 7.0%	100
B Solution	
KH_2PO_4 (0-52-34) + $NH_4H_2PO_4$ (12-61-0)	2200
$MgSO_4{\cdot}7H_2O$ (MgO 16%, S 16%) + KNO_3 (13-0-46)	5500
Mn-EDTA 13.0% + $NiSO_4{\cdot}6H_2O$ 22.3%	50
Nicsprays (MgO 7.29%, Fe 1.9%, Mn 1.94%, Cu 2.08%, Zn 1.9%, B 2.17%, Mo 0.024%)	250

2.4. Experimental Design, Greenhouse, and Planting Tables

A two-sample *t*-test was used in this experiment. NFT-Hydroponic with IoT was the test group, whereas conventional NFT-Hydroponic was the control group. The sample plants in each group were randomized for 10 plants (replications) to record each parameter (plant height, stem diameter, leaf number, leaf width, leaf length, leaf area, root length, fresh weight, dry weight, nitrate accumulation, and chlorophyll content). The plants were randomized to ensure no inherent bias towards either group.

The closed-type greenhouse structure for experimentation located at the Agricultural Innovative Demonstration and Development Center in Honor of Rama IX (8°38′29.5″ N 99°53′42.6″ E), Walailak University, Nakhon Si Thammarat, Thailand, has dimensions of 6 m in width, 12 m in length, and 3.5 m in height. The chosen vegetable for cultivation is Chinese cabbage, which is a larger and taller plant, making it suitable for experimental cultivation. The cultivation timeline spans from seed germination to harvest, taking approximately 35 to 42 days. Within the greenhouse, a water pump (Sonic AP 3500, 60 W) is installed to control the delivery of nutrient solutions to the plants. Digital devices for monitoring temperature and humidity are also set up, along with shading devices to mitigate excessive sunlight, which could result in increased internal heat within the greenhouse.

The planting tables have dimensions of 1.80 m in width, 6.00 m in length, and 0.90 m in height. Each planting table accommodates 9 planting rows, and a total of 261 plants can be grown per table. A water pump is responsible for circulating nutrient solutions through the plant roots and back to the solution reservoir, ensuring the circulation of nutrients. After designing and installing the control system within the greenhouse, preliminary tests are conducted to fine-tune any potential shortcomings. These tests include parameter adjustments, data collection, and the visualization of results.

2.5. Seedling Preparation

We selected mature seeds of Chinese cabbage (*Brassica pekinensis* Rupr.) of the variety "Jia Tai" by choosing seeds that are healthy and robust. To eliminate seedborne pathogens, we soaked the seeds in a solution of 10% sodium hypochlorite (NaOCl) for 1 min. Afterward, we rinsed the seeds thoroughly with distilled water. Next, we initiated the germination process by placing the seeds in 100 milliliters of distilled water, oxygenated with microbubbles, for 24 h. This should be performed in a light-free environment at a temperature of 25 °C.

Once the roots started to germinate, we placed the germinated seeds in hydroponic sponges with a fine-grade A texture measuring 1 × 1 × 1 inch. We placed one seed per sponge and inserted it into trays for seedling cultivation. We filled the sponges with water that had been filtered daily, maintaining a volume of 100 milliliters to preserve moisture in the sponges for 3 days. Afterward, we added nutrient solution diluted to 50% strength of the regular hydroponic nutrient solution (EC 0.5 mS cm^{-1}, pH 6.0), at a rate of 100 mL day^{-1}, for a period of 14 days in a closed greenhouse. In this controlled environment, the seedlings were transplanted into planting cups on the 15th day for further hydroponic cultivation (Figure 3). The hydroponic seedling cultivation process involves transitioning the seedlings in the evening hours to help them acclimate to the new environment, particularly during the cooler nighttime temperatures. The roots of the plants come into contact with the nutrient solution in the growing channels. Prior to transplanting the seedlings, the growing channels should undergo sterilization using a 10% sodium hypochlorite solution to eliminate pathogens. Additionally, we ensured thorough cleaning by rinsing to prevent root rot and damping-off diseases during the growth phase.

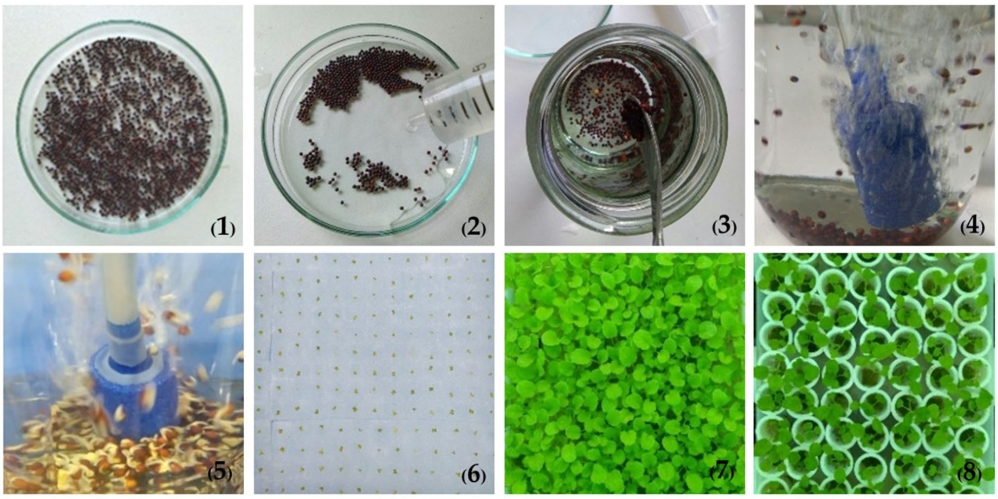


Figure 3. The steps involved in preparing seedlings of Chinese cabbage for hydroponic cultivation: (1) seed selection; (2) seed disinfection; (3) soaking seeds in distilled water; (4) oxygenation; (5) 1-day-old germinated seed; (6) germination in a sponge with water; (7) 14-day-old seedlings; and (8) transplanting seedlings into planting cups.

2.6. Data Collection

The data collection was divided into two parts. The first part involved measuring parameter values using handheld measuring tools. These measurements include pH, EC (Electrical Conductivity), air temperature, water temperature, humidity, and light intensity. The second part of data collection pertains to plant growth data, which includes measurements such as plant height, stem diameter, leaf width, leaf length, and chlorophyll content. These data were collected daily from the beginning of the planting process until the harvesting day. A representative sample of 10 Chinese cabbage plants was measured throughout the cultivation period. Additionally, plant samples were collected every three days to determine fresh and dry weights over the cultivation period.

After a cultivation period of 42 days, the accumulated nitrate content of the harvested Chinese cabbage plants was measured. The growth data and parameter values were documented and graphed, including pH, EC, air temperature, water temperature, humidity, and light intensity. The software recorded these data, making it accessible for analysis throughout the cultivation period. Furthermore, for leaf area analysis, Adobe Photoshop CS6 was utilized to calculate the leaf surface area from the obtained images. This process contributed to assessing the growth and development of the plants throughout the experiment.

2.7. Measuring Accumulated Nitrate Content

To measure the accumulated nitrate content of the plants, we used the Greentest ECO 5 device (Greentest, Shenzhen, China). We started by setting the device to "Chinese Cabbage", and then inserted the probe into the soil at the base of the Chinese cabbage plant. We then pressed the measurement button. Alternatively, for measuring nitrate content in the leaves of Chinese cabbage, one can follow these steps: Crush and macerate the Chinese cabbage leaves to extract the sap; strain the sap to separate the liquid from the solid matter; immerse the probe of the nitrate measurement device into the sap; read the results displayed on the device's screen. If the value displayed on the screen is green with the message "PASS-Low Nitrate Content", it means the nitrate content is within the standard range set by the device, indicating that the product is safe. If the value is orange, it suggests slightly elevated nitrate levels, recommending consumption in limited quantities. If the screen turns red, indicating high nitrate content beyond the standard range, it is advised not to consume the produce, as it may not be safe for consumption. This device helps assess the nitrate safety of the harvested Chinese cabbage, ensuring the quality and safety of the produce for consumers.

2.8. Data Analysis

The experimental data for the growth and yield parameters were analyzed using IBM SPSS Statistics Version 23. An independent two-sample *t*-test was used to compare the means of NFT-Hydroponics with IoT (test group) and conventional NFT-Hydroponics (control group) for each measured parameter. This analysis was conducted at a 95% confidence level to determine whether there were any statistically significant differences between the two groups.

3. Results

3.1. Internet of Things (IoT) Utilization

The IoT system effectively controlled environmental parameters within the hydroponic setup. The user interface facilitated remote monitoring and adjustments of pH and nutrient solution levels through a computer or smartphone.

Controlling the operational aspects of the IoT system can be effectively managed through a computer acting as the central controller. The operational interface is visualized in Figure 4, accessible through the primary navigation bar located on the left side, while the outcomes and results are presented on the right-hand side. The main landing page, referred to as the Home page, furnishes an overview of the dashboards, which can be categorized and labeled according to specific tasks within the hydroponic experimentation plots.

Once accessed, a comprehensive representation of multi-parameter insights can be observed through semicircular and line graphs. Simultaneously, the latest values for the Timeseries Table are depicted, constantly updating the present Timeline metrics. System regulation is facilitated by the activation of buttons designed to administer the nutrient solution and adjust pH levels using acid–base solutions. During the operational phase, after the introduction of substances into the system, a waiting period of approximately 30 s is advisable to allow thorough mixing of the solution until stability is achieved. At this point, the displayed value can be recorded to obtain an accurate post-adjustment reading. It is recommended to release Solution A and Solution B in equal proportions, employing a timed sequence. To minimize precipitation, Solution A should be introduced into the system roughly 30 s prior to dilution, enabling effective blending and the subsequent introduction of Solution B.

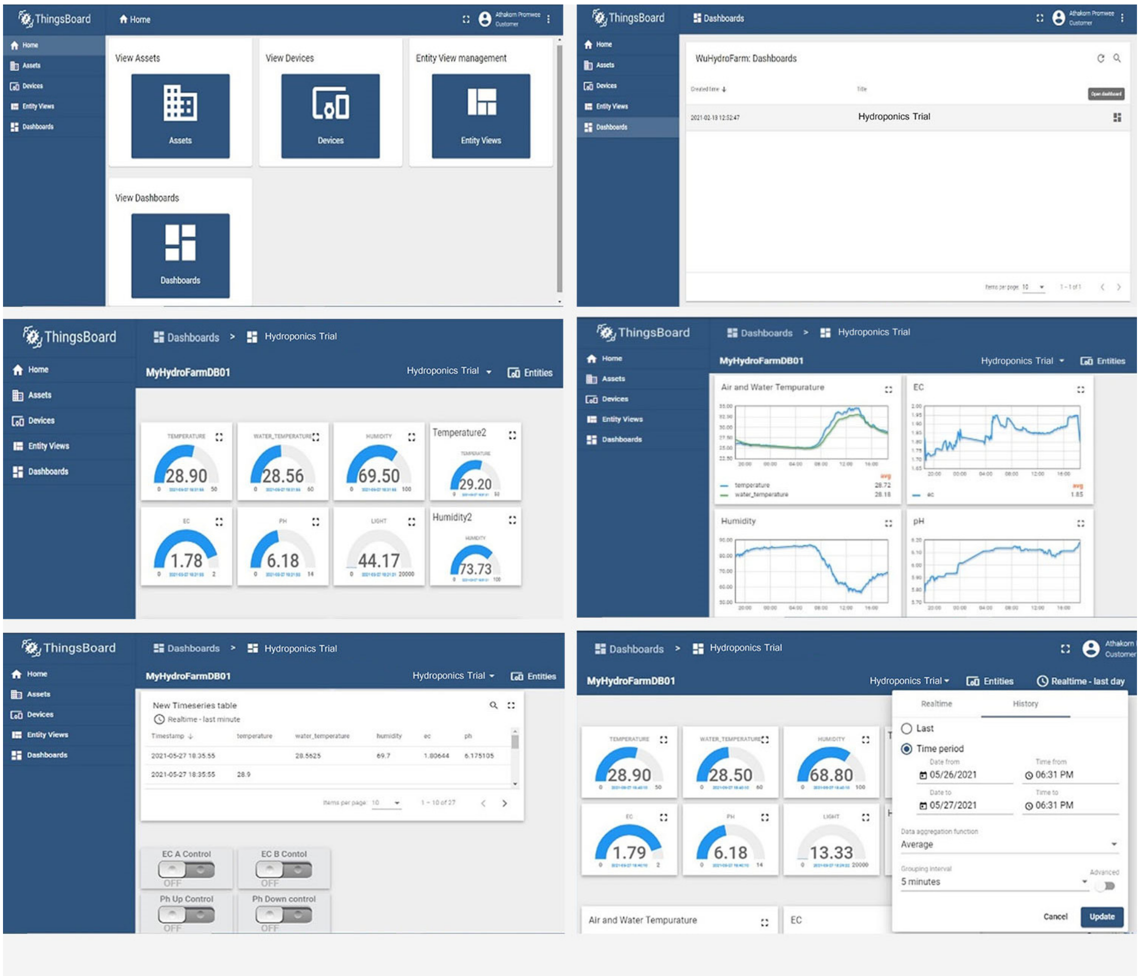


Figure 4. The display screen for controlling the IoT system with a computer.

Furthermore, apart from computer-based control, this system offers the convenience of smartphone operation, which, while providing ease of use, comes with a slightly narrower screen display compared to a computer. Nevertheless, it maintains equivalent controllability, as illustrated in Figure 5, making it an invaluable tool for on-the-go accessibility at any time and any place.

Through practical usage, it was observed that the pH value undergoes changes approximately 6–10 h after the most recent adjustment. Consequently, it is recommended to inspect the system via the mobile screen in the morning and evening for EC value adjustments and to ensure that pH levels do not elevate excessively by incorporating acid. This acid addition should be administered gradually, allowing for meticulous pH fine-tuning to achieve the desired levels, as monitored through the display screen.

While in operation, if a power outage occurs, the recording of the most recent measurement will halt. However, upon power restoration, the measurement process will automatically resume without requiring a system reset. Moreover, upon completion of the task, the history feature can be employed. By specifying the desired time range within the Time Period option, users can access historical graphical data. These data can be examined with precision to two decimal places by interacting with the graph. Consequently, the program will promptly present the date and time corresponding to the data point, ensuring user-friendly data interpretation.

Figure 5. The display screen for controlling the IoT system with a smartphone.

3.2. Experiment Results Regarding Parameters

3.2.1. pH and EC

The IoT system maintained pH within the optimal range of 6.0–6.5, while manual adjustments in the conventional system resulted in occasional fluctuations. Similarly, EC values were managed effectively using the IoT system, ensuring optimal nutrient availability throughout the growth cycle.

The comparison was made between cultivating Chinese cabbage through conventional hydroponics, utilizing manual control of cultivation conditions with parametric instruments, and employing an automated parameter measurement IoT system. The outcome of the production system control experiment is illustrated in Figure 6a. It was observed that the manual pH values (A-Normal) in traditional production were consistently higher throughout the cultivation period and dipped to 6.5. During days 15, 22, 29, and 36, the pH was adjusted weekly to achieve the optimal range, as systemic pH values exceeding 7.0 and peaking at 8.5 were detrimental to plant growth. Conversely, the measured values of the IoT manufacturing system, both manual (B-Manual) and automated (B-IoT), showed a mere 0.2% difference. The probe values of the IoT system were substantial.

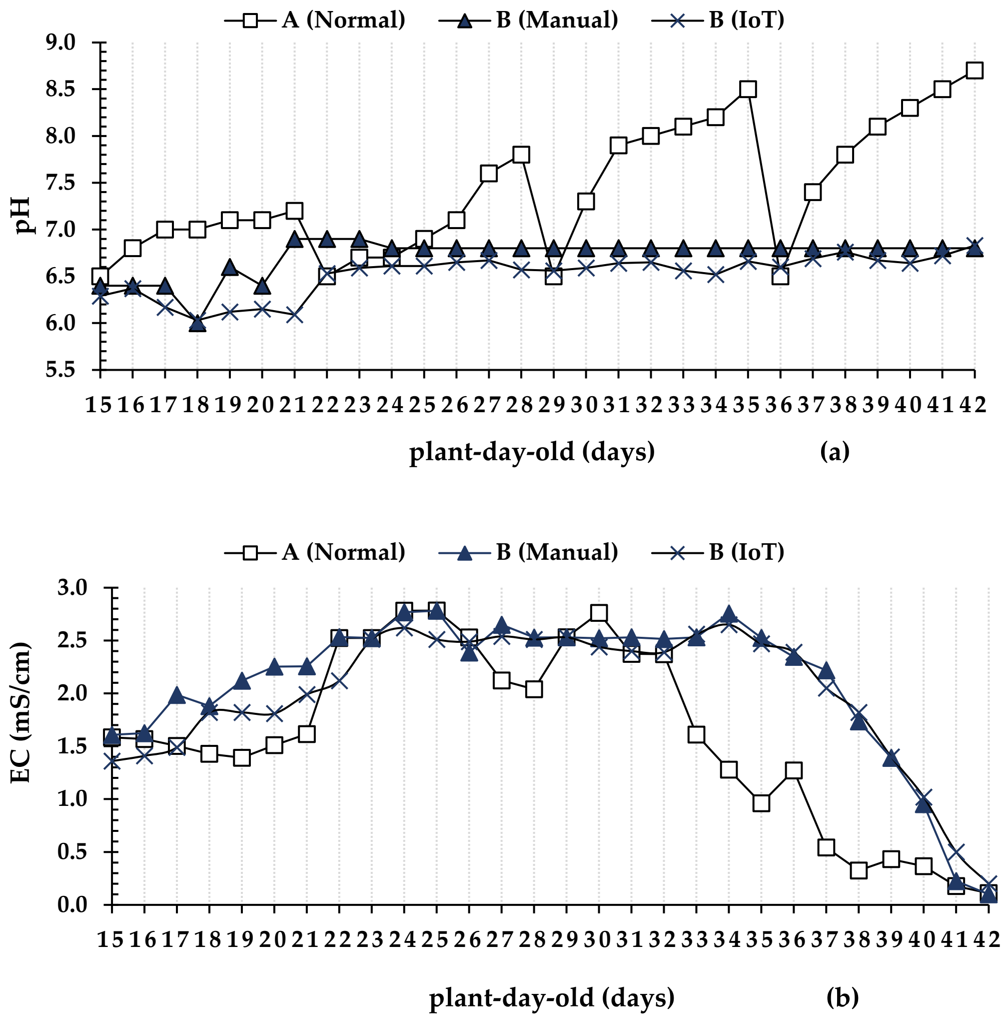


Figure 6. Chinese cabbage cultivation environment, pH (**a**), and EC (**b**) with conventional hydroponic system (A-Normal) compared with growing with IoT system (B-IoT) at 15 to 42 days old.

In the initial week, the system's pH measurements fluctuated more than after the 22nd day, attributed to the early phase of system control. Inexperienced users adjusting acid and base emissions led to values less stable than desired. However, they were maintained within the optimal range of 7.0, which did not adversely affect the root system and Chinese cabbage growth. Thus, if pH adjustments are not made, the pH may surge, creating unfavorable conditions for plant growth.

For nutrient solution addition, A-Normal solution was supplemented every 7 days, resulting in higher EC values on days 15, 22, 29, and 36, as depicted in Figure 6b. During weeks without nutrient solution addition, EC values gradually declined due to plant deployment, significantly decreasing in weeks 3 and 4 compared to manual IoT production (B-Manual) and automatically measured (B-IoT), differing by only 0.1. The values were carefully controlled to decline slowly and steadily to prevent malnutrition. As growth progressed, EC reduction in the final week aimed to maintain accumulated nitrate levels within a safe range for consumers before harvest.

3.2.2. Air Temperature, Water Temperature, Humidity, and Light

The IoT system continuously monitored these environmental parameters, revealing their influence on plant growth. Measured values aligned with expectations and provided insights into the overall growing conditions.

Comparing external air temperatures to greenhouse temperatures, outdoor air was 1–2 °C higher, while indoor air and water temperatures were approximately 1–2 °C apart.

Most values were similar, as they corresponded to water temperature. High air temperatures correlated with high water temperatures, and vice versa, as displayed in Figure 7a,b, respectively. These values were inversely related to humidity; high temperatures correlated with low humidity, and low temperatures correlated with high humidity, as shown in Figures 7a and 8a, respectively. While outside humidity differed from indoor humidity on particularly hot days, air and water temperatures in the experimental greenhouse remained consistent. Conventional (A-Normal) cultivation values aligned with manual IoT production (B-Manual) and B-IoT-measured IoT production.

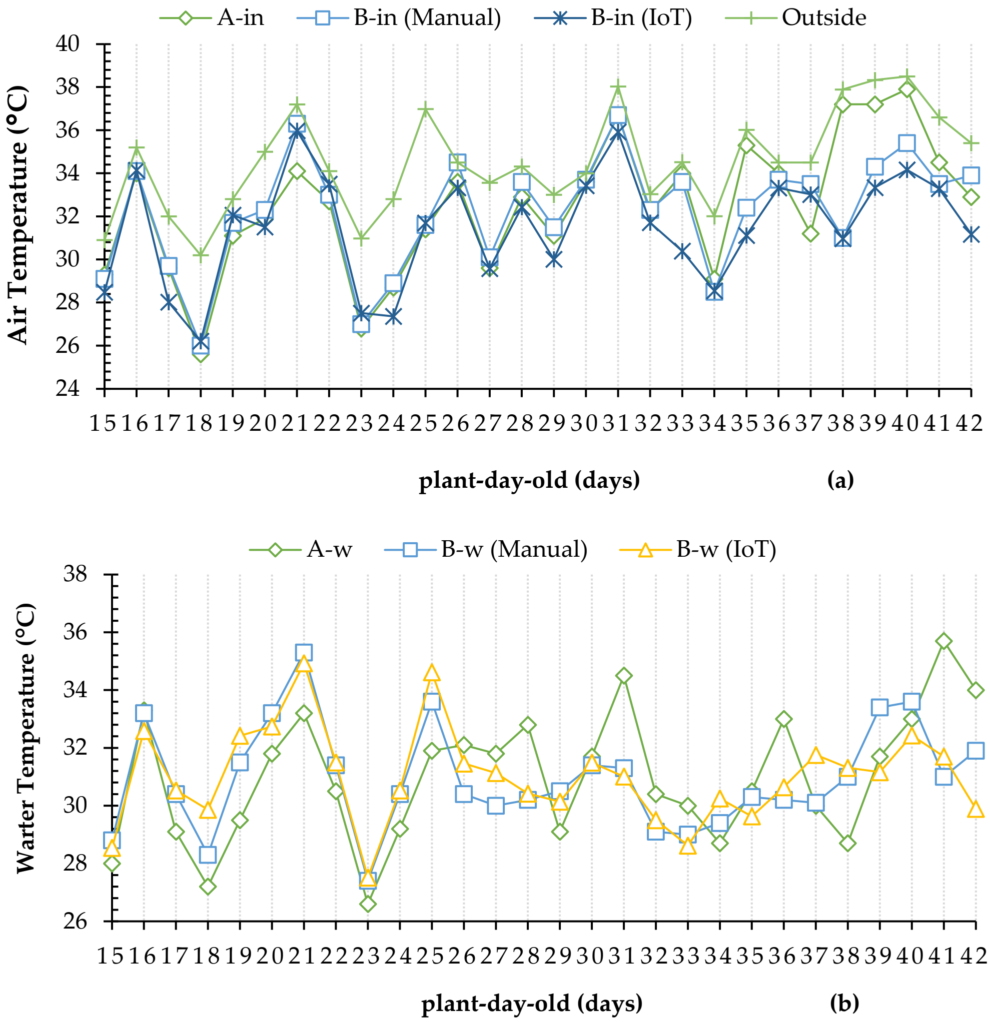


Figure 7. Chinese cabbage cultivation environment, air temperature (**a**) and water temperature (**b**) with conventional hydroponic system (A-Normal) compared with growing with IoT system (B-IoT) at 15 to 42 days old.

Regarding light intensity, exterior levels were 1–3 times higher than interior levels on certain hot days. Values measured manually in conventional cultivation (A-Normal) closely matched manual measurements of IoT production (B-Manual). However, IoT system measurements slightly differed, ranging from 3000–5000 Lux. This discrepancy could be due to measurement points. Manual measurements were taken at mid-level within the test plot, while IoT measurements were at the far end due to plant height. Additionally, exposure time slightly differed, leading to varying measurements. Overall, light exposure varied throughout the day, and the IoT system continuously collected high-resolution data every 5 s during the experiment, as shown in Figure 8b.

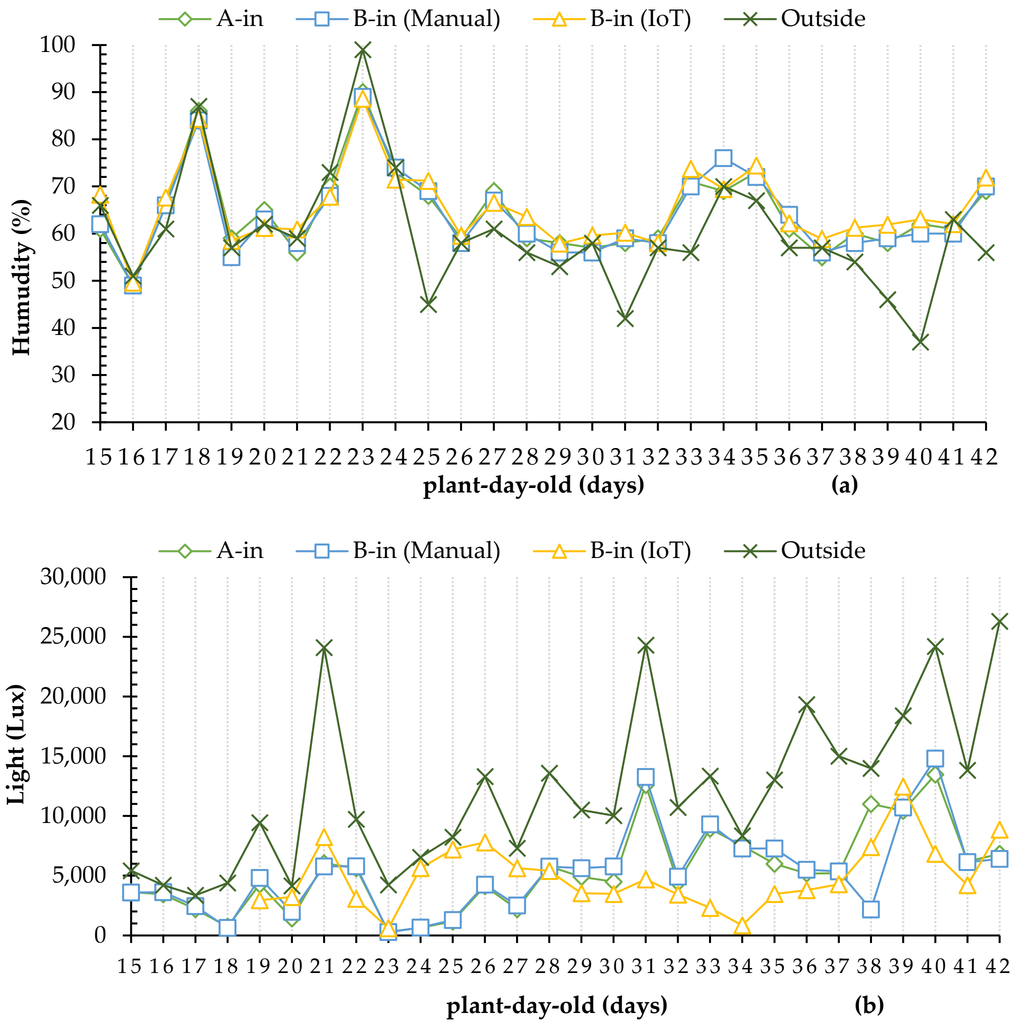


Figure 8. Chinese cabbage cultivation environment, humidity (**a**) and light (**b**) with conventional hydroponic system (A-Normal) compared with growing with IoT system (B-IoT) at 15 to 42 days old.

Cultivation through the IoT system maintained pH within the optimal range of 6.0–6.5, preventing it from exceeding 7.0, which could hinder plant growth. Similarly, EC values were managed, starting at 1.0–1.5 in the first week and gradually rising to 2.0–2.5 in the second. The range was maintained at 2.5 during the third week, decreasing to 0.3 in the fourth, equivalent to plain water's EC value. In terms of air temperature, the greenhouse air temperature was 1–2 degrees higher than the average water temperature, with a direct proportionality during the experiment. The highest temperature reached 36 °C and decreased to around 34 °C in the final two weeks. Additionally, water and air temperatures showed an inverse relationship with humidity throughout the entire cultivation period. Measured light intensity peaked at 35,000 lux on scorching days and dropped to as low as 10,000 lux on rainy days, while it reached zero during the nighttime hours.

3.3. Growth Comparison and Quality Assessment of Chinese Cabbage

Plants grown with the IoT system exhibited significantly greater height, stem diameter, leaf width, and leaf length compared to those grown conventionally. This indicates improved overall growth and development.

3.3.1. Plant Heights

During the initial two weeks, both NFT hydroponic systems, with and without IoT, exhibited similar plant heights. However, in the subsequent two weeks, plants cultivated with IoT displayed a significant increase in height, measuring 3–4 cm more than the control group. By the 42nd day, the plants with IoT reached a significant height of 39.70 cm, surpassing the control group's 35.72 cm, representing an 11.14% elevation ($p < 0.05$) (Figure 9).

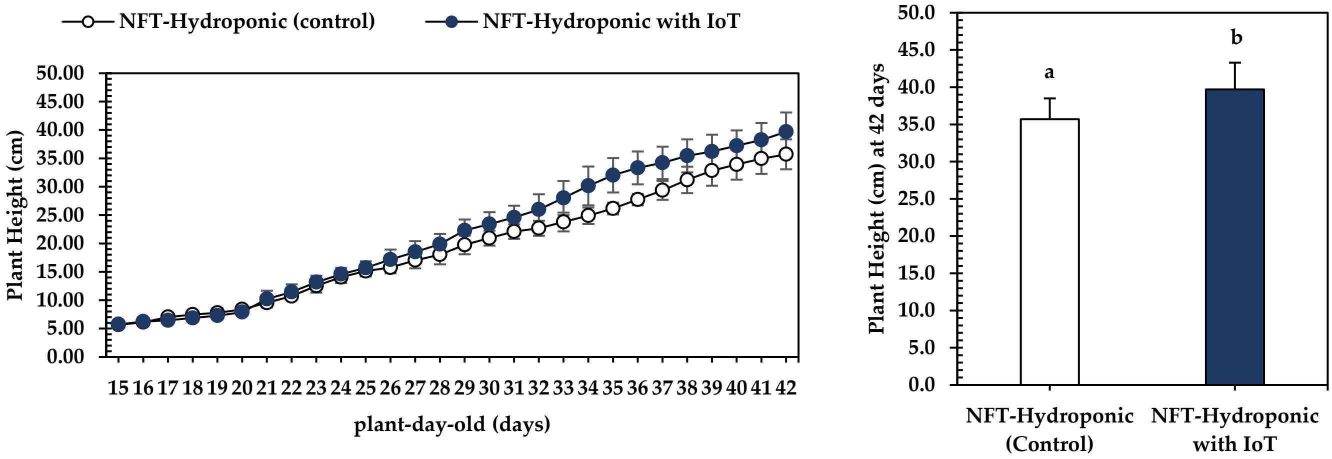


Figure 9. Plant height of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 15 to 42 days old. The error bars likely represent each group's standard deviation of the plant height. Mean values commanded by the different letters (a,b) are significantly different according to an independent two-sample *t*-test ($p < 0.05$).

3.3.2. Stem Diameter

Over the last two weeks, stem diameter increased by 0.1–0.3 cm more in plants grown with IoT compared to control plants. At 42 days, the average stem diameter in IoT-grown plants (1.01 cm) was significantly larger than conventionally grown ones (0.76 cm), indicating a notable increase of 32.89%, with a *p*-value less than 0.05 ($p < 0.05$) signifying a statistically significant difference (Figure 10).

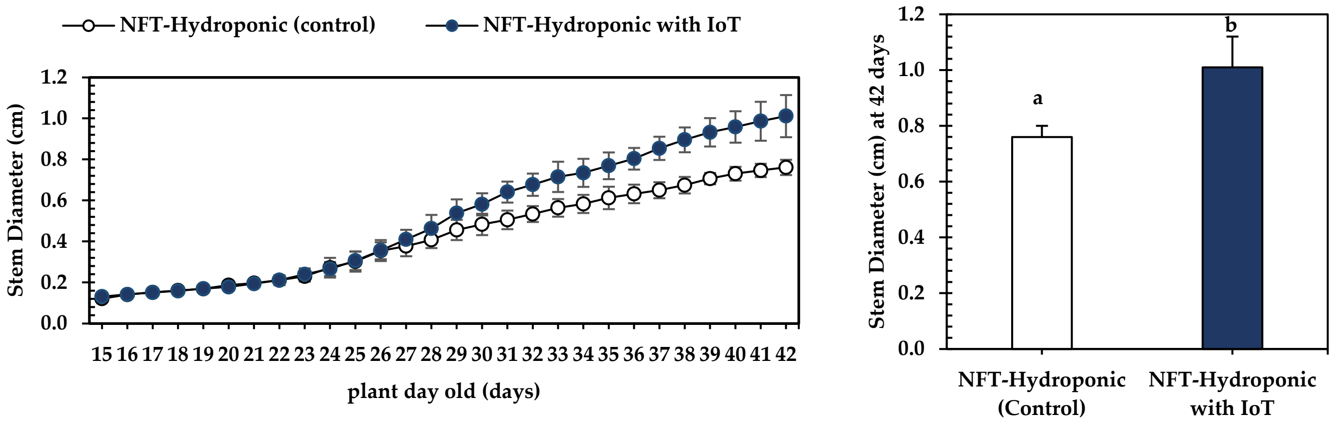


Figure 10. Stem diameter of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 15 to 42 days old. The error bars likely represent each group's standard deviation of the stem diameter. Mean values commanded by the different letters (a,b) are significantly different according to an independent two-sample *t*-test ($p < 0.05$).

3.3.3. Leaf Number

Leaf count remained similar in both systems for the first 3 weeks. IoT-grown cabbage showed a slight increase in leaf count (1–2 more leaves) in the last week. However, by the 42nd day, the average leaf count did not show a significant difference between the groups (20.00 for IoT, 21.40 for conventional, $p > 0.05$) (Figure 11).

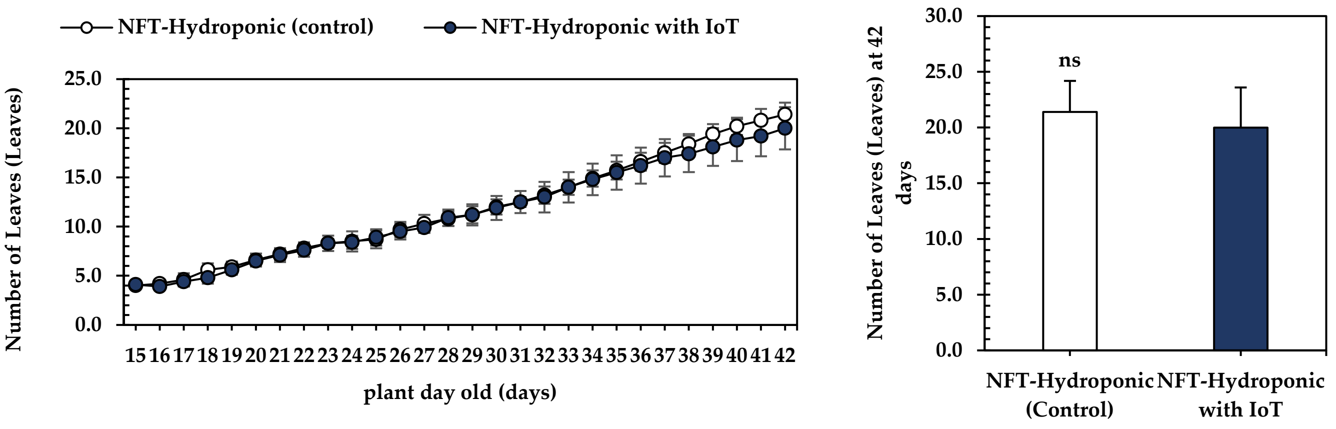


Figure 11. Leaf number of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 15 to 42 days old. The error bars likely represent the standard deviation of the leaf number for each group. Mean values commanded by the ns are not significantly different according to an independent two-sample *t*-test ($p > 0.05$).

3.3.4. Leaf Width and Leaf Length

In the initial two weeks, both systems produced leaves with similar widths and lengths, with minimal differences in the growth rate. However, in the subsequent weeks, leaf width and length in the conventional system seemed to stabilize and lag behind the IoT system. At 42 days, the average leaf width of IoT plants (18.61 cm) was significantly larger ($p < 0.05$) than the conventional group (14.06 cm), representing a 32.36% increase (Figure 12). Similarly, the average leaf length of IoT plants (21.05 cm) was significantly longer ($p < 0.05$) than the conventional group (15.24 cm), representing a 38.12% increase (Figure 13).

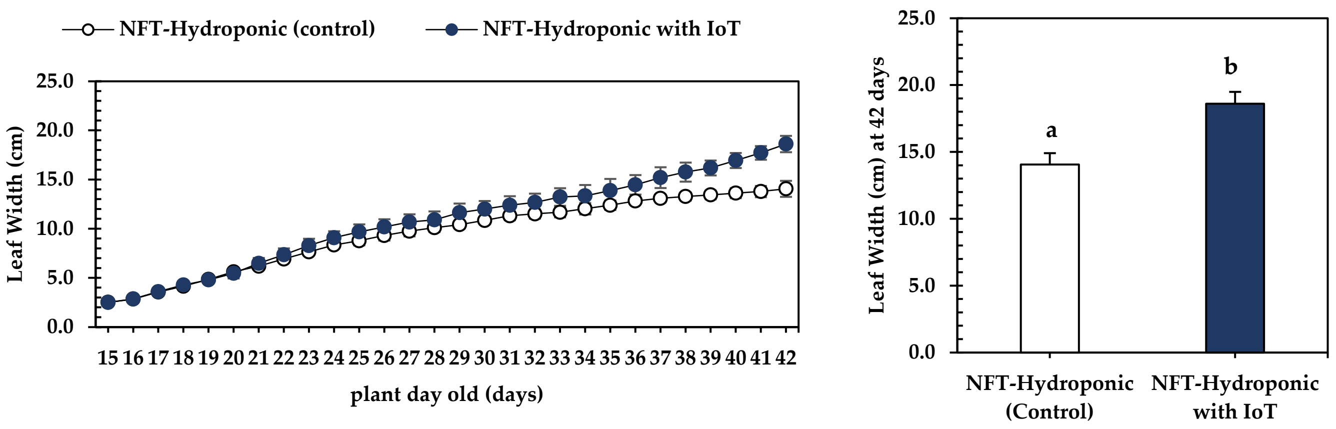


Figure 12. Leaf width of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 15 to 42 days old. The error bars likely represent each group's standard deviation of the leaf width. Mean values commanded by the different letters (a,b) are significantly different according to an independent two-sample *t*-test ($p < 0.05$).

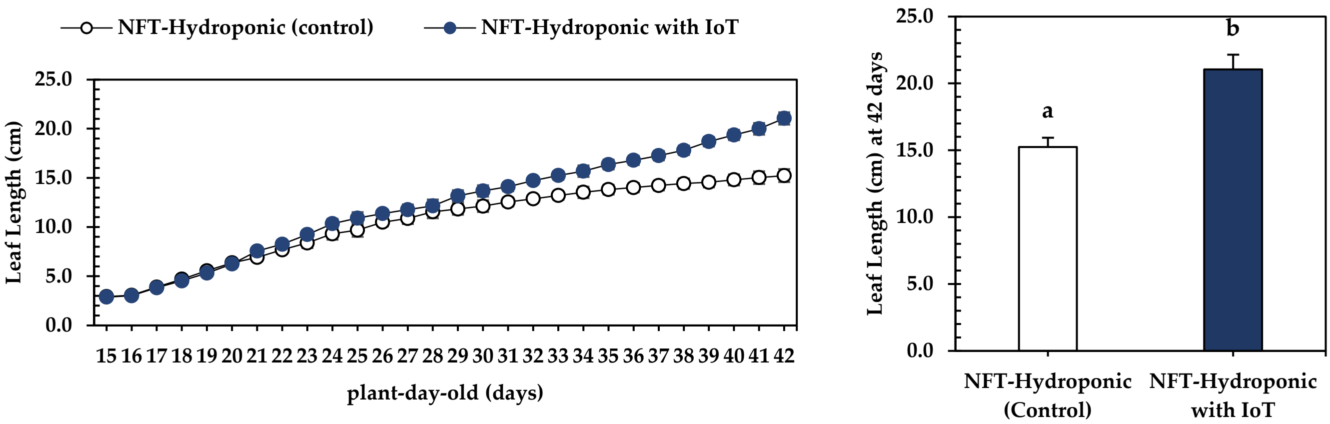
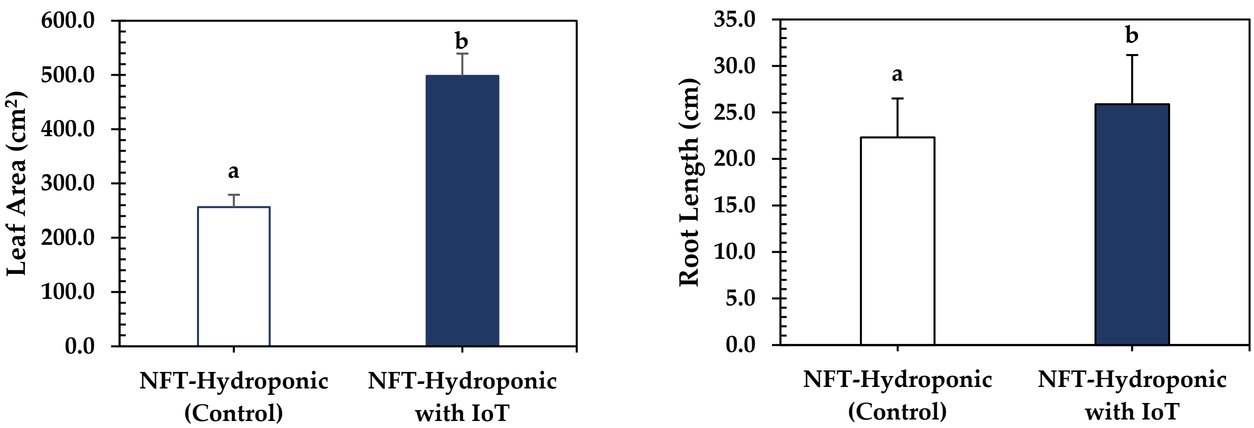


Figure 13. Leaf length of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 15 to 42 days old. The error bars likely represent each group's standard deviation of the leaf length. Mean values commanded by the different letters (a,b) are significantly different according to an independent two-sample *t*-test ($p < 0.05$).

3.3.5. Leaf Area and Root Length

Leaf area was significantly larger in IoT-grown plants, suggesting increased photosynthetic potential and yield. A comparison between Chinese cabbage leaves cultivated using conventional and IoT systems revealed marked distinctions in leaf area. Leaves produced by the IoT system were notably larger, measuring twice the size of those from the conventional system. Positioned at a mid-level within the canopy, these leaves benefited from optimal light exposure and displayed an appropriate level of maturity, striking a balance between being too mature and excessively tender. Furthermore, the width of the leaf petiole in the midsection of the leaf within the IoT system exceeded that of the conventional system, contributing to the desired crispness required in the market. By the 42nd day, the average leaf area of plants grown with IoT reached 498.38 cm^2, significantly surpassing the conventionally grown counterparts at 256.50 cm^2. This substantial increase of 94.30% is highlighted by a *p*-value of less than 0.05 ($p < 0.05$), indicating a statistically significant difference (Figure 14a).



(**a**) (**b**)

Figure 14. Leaf area (**a**) and root length (**b**) of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 15 to 42 days old. The error bars likely represent each group's standard deviation of the leaf area and root length. Mean values commanded by the different letters (a,b) are significantly different according to an independent two-sample *t*-test ($p < 0.05$).

Root length also increased with the IoT system, indicating improved nutrient uptake and plant stability. The root growth observed in both production systems demonstrated similar quality, with no apparent symptoms of root rot or damping-off disease. Root color remained consistent across the upper and lower parts of the plants, showing no significant differences. However, the density of root volume was higher in the upper portion compared to the lower portion, and in certain instances, the inner roots of cabbage heads could intertwine due to the restricted growth space. During harvesting, when cabbage heads are pulled up, there is a chance that inner root tips may occasionally break off. By the 42nd day, the average root length of plants cultivated with IoT measured 25.89 cm, significantly surpassing the conventional counterparts at 22.33 cm. This marked increase of 15.94%, along with a p-value of less than 0.05 ($p < 0.05$), indicates a statistically significant difference (Figure 14b).

3.3.6. Fresh Weight and Dry Weight

Both shoot and root fresh and dry weights were significantly higher in IoT-grown plants, demonstrating enhanced biomass production. At 42 days old, the shoot fresh weight of plants nurtured with IoT (346.54 g plant^{-1}) showcased a significant increase in comparison to those cultivated conventionally (270.54 g plant^{-1}). This notable difference indicated a substantial 28.09% increase, with a p-value of less than 0.05 ($p < 0.05$), underscoring a statistically significant distinction (Figure 15a). Conversely, the root fresh weight of plants with IoT (6.39 cm) did not exhibit a significant difference when compared to those grown conventionally (7.06 g plant^{-1}) ($p > 0.05$) (Figure 15b). The total fresh weight of plants with IoT (352.93 g plant^{-1}) surpassed those grown conventionally (277.60 g plant^{-1}) significantly. This substantial increase of 27.14% was substantiated by a p-value of less than 0.05 ($p < 0.05$), indicating a statistically significant difference (Figure 15c). Moving on to the shoot dry weight, plants cultivated with IoT (31.23 g plant^{-1}) displayed a significant increase in comparison to conventionally grown ones (20.96 g plant^{-1}). This marked difference represented a notable 48.99% increase, with a p-value of less than 0.05 ($p < 0.05$), highlighting a statistically significant distinction (Figure 15d). Similarly, the root dry weight of plants nurtured with IoT (1.87 g plant^{-1}) exhibited a significant increase compared to conventionally grown plants (1.27 g plant^{-1}). This marked difference represented a notable 47.24% increase, with a p-value of less than 0.05 ($p < 0.05$), signifying a statistically significant distinction (Figure 15e). Concluding with the total dry weight, plants cultivated with IoT (33.10 g plant^{-1}) demonstrated a significant increase compared to those grown conventionally (22.23 g plant^{-1}). This marked difference represented a notable 48.90% increase, with a p-value of less than 0.05 ($p < 0.05$), signifying a statistically significant distinction (Figure 15f).

3.3.7. Nitrate Accumulation

At the 42−day mark, it is essential to extend our assessment beyond production-related metrics and also consider the accumulation of nitrates in cabbage, a crucial indicator of crop safety. The analysis revealed higher nitrate levels in the leaves compared to the roots. However, there was no statistically significant difference in the accumulated nitrate levels between conventionally and IoT-cultivated crops, and both fell within the acceptable range. Typically, nitrate levels should not exceed 2000 milligrams per kilogram to ensure safety for consumers. In terms of stem nitrate accumulation, plants with IoT (557 mg kg^{-1} fw) did not show a significant difference compared to conventionally grown ones (499.00 mg kg^{-1} fw) ($p > 0.05$). Similarly, leaf nitrate accumulation in plants with IoT (1910 mg kg^{-1} fw) did not significantly differ from those grown conventionally (1900 mg kg^{-1} fw) ($p > 0.05$). The total nitrate accumulation in plants with IoT (1233.50 mg kg^{-1} fw) was not significantly different from conventionally grown plants (1199.50 mg kg^{-1} fw) ($p > 0.05$). Importantly, both sets of data remained within the acceptable and safe range for consumer consumption (Figure 16).

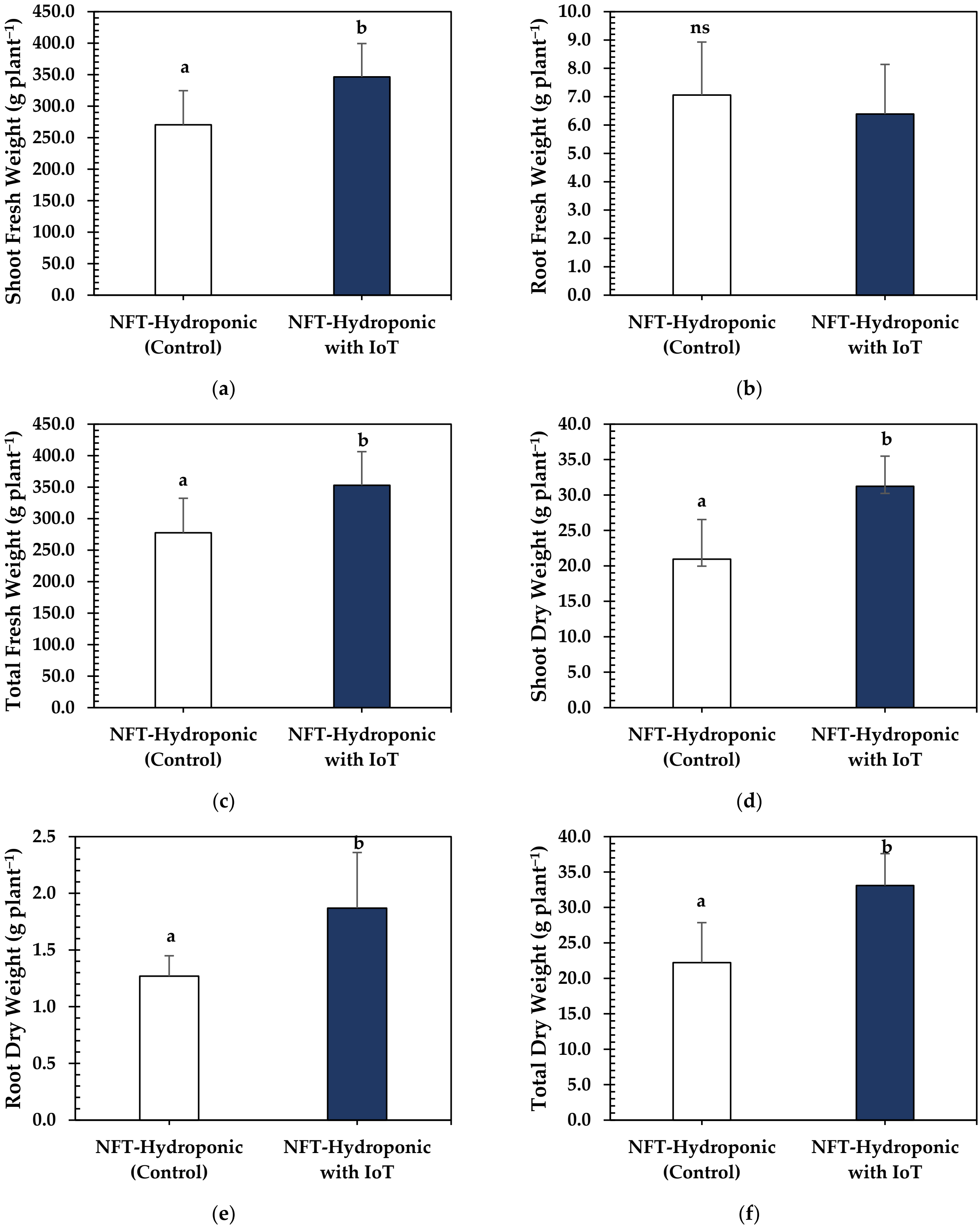


Figure 15. Shoot fresh weight (**a**), root fresh weight (**b**), total fresh weight (**c**), shoot dry weight (**d**), root dry weight (**e**), and total dry weight (**f**) of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 42 days old. The error bars are likely to represent the standard deviation of the parameters for each group. Mean values commanded by the different letters (a,b) are significantly different according to an independent two-sample t-test ($p < 0.05$). Mean values commanded by ns are not significantly different according to an independent two-sample *t*-test ($p > 0.05$).

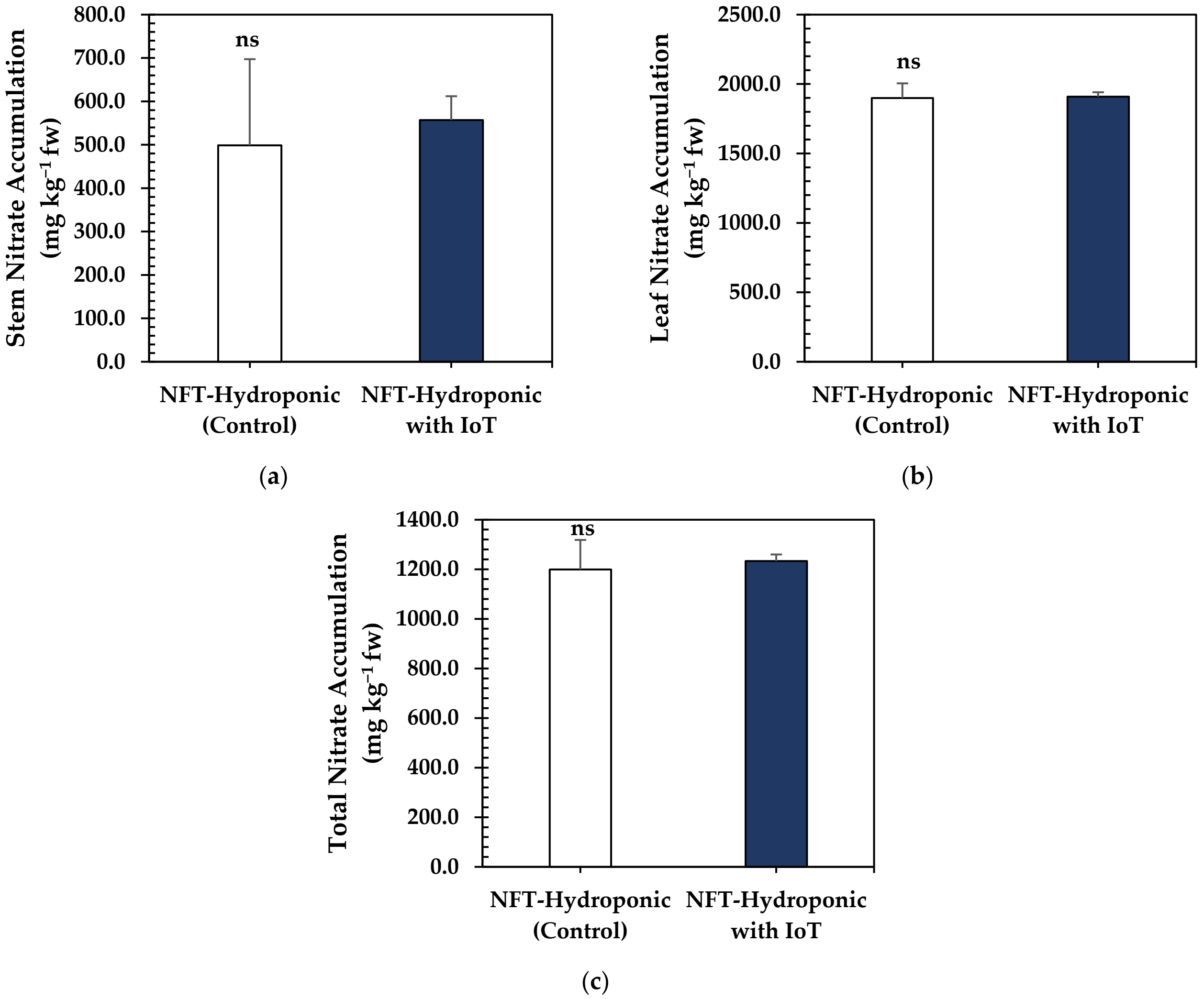


Figure 16. Stem nitrate accumulation (**a**), leaf nitrate accumulation (**b**), and total nitrate accumulation (**c**) of Chinese cabbage cultivated under NFT-Hydroponic with IoT compared with conventional NFT-Hydroponic (control) at 42 days old. The error bars likely represent the standard deviation of the parameters for each group. Mean values commanded by the ns are not significantly different according to an independent two-sample *t*-test ($p > 0.05$).

3.3.8. Chlorophyll Content

Chlorophyll content, an indicator of leaf color intensity, was significantly higher in IoT-grown plants, suggesting improved photosynthetic activity. The overall green color of cabbage leaves from both cultivation methods appeared to be within the typical range suitable for general market distribution when observed with the naked eye. However, it's important to note that the green color may not be uniform across every leaf. Chlorophyll content measurements were derived by calculating average values from various points on the leaves. Upon inspection, no diseases or insects were identified on the cabbage leaves that could disrupt the formation of green pigments.

Throughout the cultivation period, continuous measurements of chlorophyll content revealed that, under the general conventional system, nutrient solution additions occurred every week. The addition of nutrient solution on days 15, 21, 28, and 35 led to an increase in the electrical conductivity (EC) value, which correlated with a gradual rise in chlorophyll production. Chlorophyll levels tended to decrease when no additional EC value was introduced into the cultivation system. Post-harvest chlorophyll content measurements, indicating leaf color intensity, demonstrated that the chlorophyll levels of plants with IoT (30.13 SPAD) were significantly higher than those grown conventionally (24.55 SPAD). This notable increase of 22.73%, supported by a *p*-value of less than 0.05 ($p < 0.05$), highlights a statistically significant difference (Figure 17).

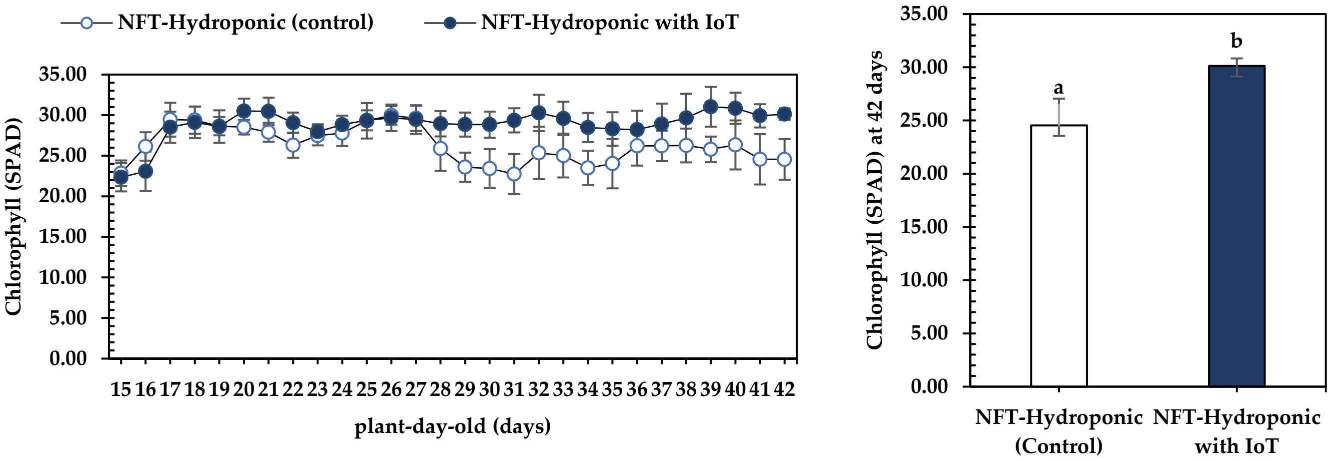


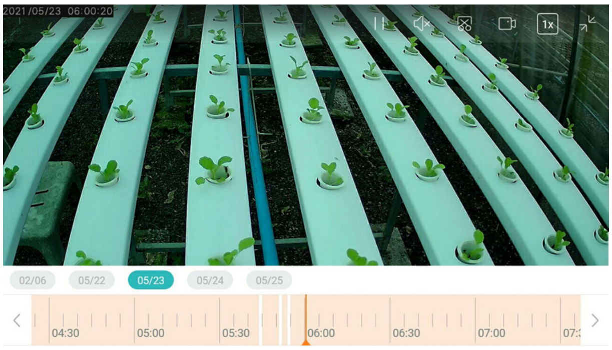
Figure 17. The comparison of chlorophyll levels in the leaves of Chinese cabbage cultivated under NFT-Hydroponic with IoT contrasted with conventional NFT-Hydroponic (control) at 15 to 42 days old. The error bars likely represent the standard deviation of the parameter for each group. Mean values commanded by the different letters (a,b) are significantly different according to an independent two-sample *t*-test ($p < 0.05$).

The characteristics of Chinese cabbage plants grown with the IoT system compared with conventional hydroponic systems 42 days after seed germination are shown in Figure 18. The growth characteristics of Chinese cabbage from the age of 15 days to 42 days through a closed-circuit camera are shown in Figures 19 and 20. At 15 days old, Chinese cabbage plants typically begin to exhibit organized growth patterns, with initial branching and the emergence of tender true leaves; however, roots remain small and there is no clear sign of lateral root development. By 21 days old, the plants experience rapid growth, with leaves increasing in size and the central bud showing increased branching and lateral bud formation, while lateral roots may start to show clearer development. At 28 days old, Chinese cabbage continues to grow steadily, with denser leaves and a larger central bud exhibiting increased branching and lateral bud development. By 35 days old, plants exhibit rapid growth, with significantly larger leaves and central buds, and signs of a well-developed and robust root system become evident. Finally, at 42 days old, Chinese cabbage plants reach their peak growth, characterized by extensive branching and lateral bud development, dense and large leaves, and a well-developed root system.

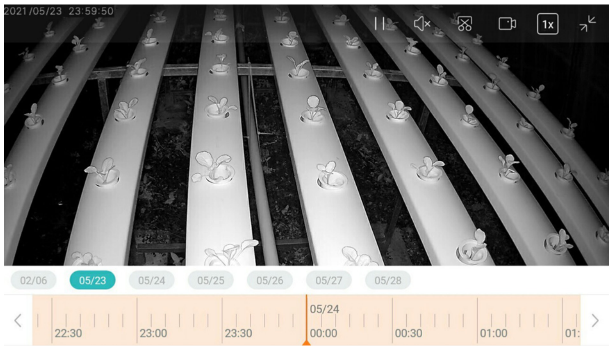
(**a**) NFT-Hydroponic (Control)

(**b**) NFT-Hydroponic with IoT

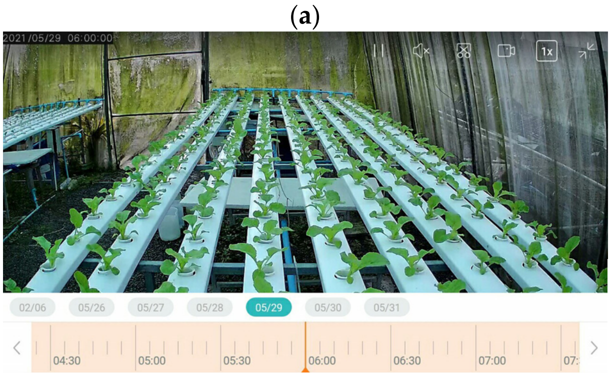
Figure 18. A visual comparison of Chinese cabbage plants after harvest, showcasing the conventional hydroponic system (**a**) alongside the IoT system (**b**) at 42 days from seed germination.



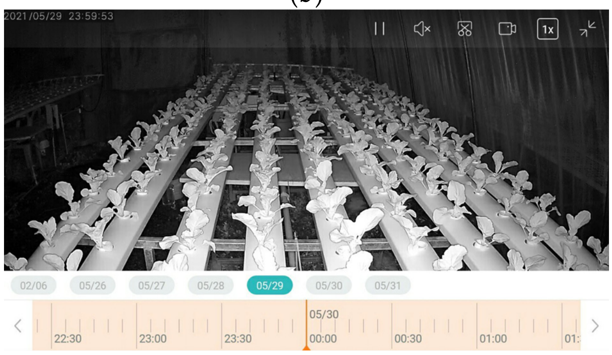
(**a**)



(**b**)



(**c**)



(**d**)

Figure 19. The growth characteristics of Chinese cabbage from the age of 15 days and 21 days through closed-circuit camera. (**a**) 15 days olds at day time, (**b**) 15 days olds at night time, (**c**) 21 days olds at day time, and (**d**) 21 days olds at night time.

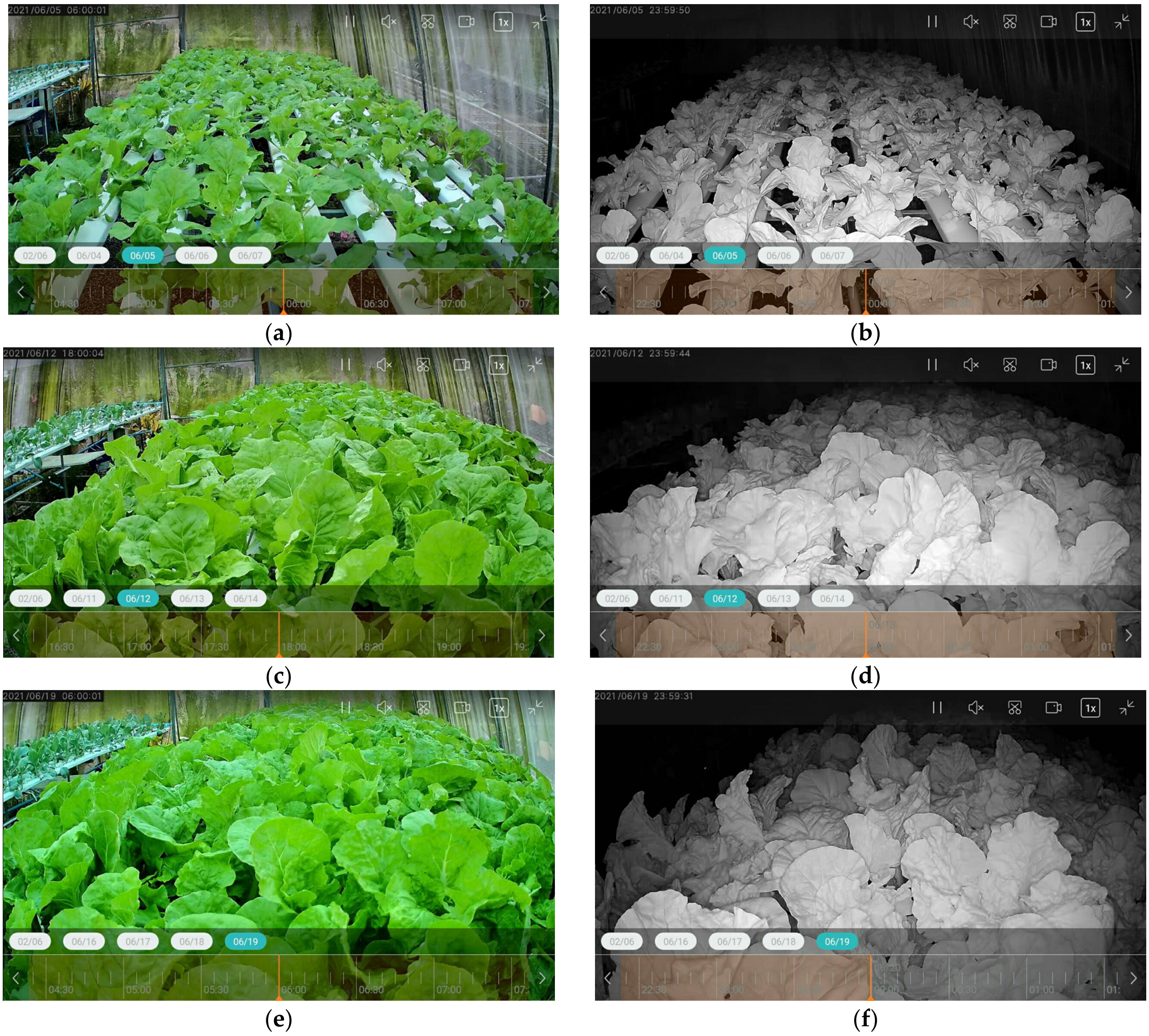


Figure 20. The growth characteristics of Chinese cabbage from the age of 28 days to 42 days through closed-circuit camera. (**a**) 28 days olds at day time, (**b**) 28 days olds at night time, (**c**) 35 days olds at day time, (**d**) 35 days olds at night time, (**e**) 42 days olds at day time, and (**f**) 42 days olds at night time.

4. Discussion

The findings demonstrate that the IoT system effectively controlled environmental parameters and promoted the superior growth and yield of Chinese cabbage compared to the conventional hydroponic method. This technology has the potential to optimize resource utilization, reduce waste, and ensure consistent production of high-quality crops.

The benefits of using an IoT system for Chinese cabbage production include faster harvesting, convenience and reduced labor, safer operation, reduced environmental impact, increased yield and quality, and improved accuracy and precision (Figure 21).

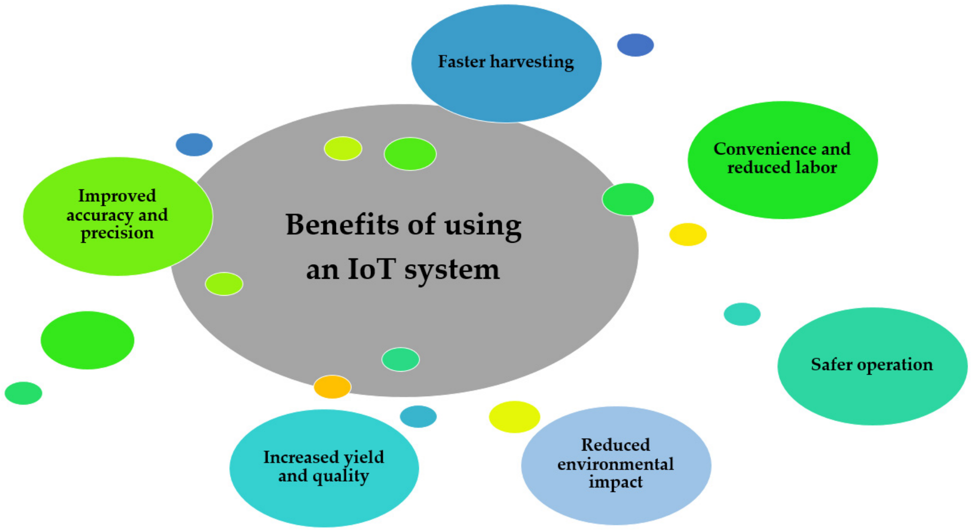


Figure 21. The benefits of using an IoT system for Chinese cabbage production.

Through the utilization of the IoT system, it was observed that the system's functionality remains consistent whether accessed through a smartphone or a computer. This uniformity is attributed to the high-speed internet connection, ensuring continuous and uninterrupted system operation. Moreover, the different sensors within the system function with precision, a result of thorough inspection and pre-configuration prior to use. The parameter measurements obtained from these sensors are more precise compared to conventional manual measurements, providing continuous and reliable data.

Furthermore, the IoT system offers greater convenience in operation compared to manual measurements, which often require the use of various tools and can be complex. Additionally, manual measurements can be cumbersome, involving multiple tools and a complex process. Moreover, manual measurements often necessitate the involvement of multiple tools and can be a labor-intensive process. In contrast, the IoT system streamlines the process and reduces the chances of errors.

It is important to note that when conducting manual measurements, there is a risk of exposure to concentrated acidic or basic solutions, which may cause skin irritation or harm if it comes into contact with the skin or eyes. Thus, precautions should be taken, such as wearing gloves or protective eyewear, to prevent such risks during manual measurement procedures.

When comparing the automated system's operation, which is inherently safer due to the reduced need for human contact with solution substances, it becomes apparent that the operations are much more convenient. This is because the solutions are pre-packaged in containers, eliminating the need for direct handling. Consequently, the workflow becomes notably more convenient. Simply by issuing commands through a smartphone or computer, tasks can be executed without the necessity of being present at the farm area.

The ability to remotely control the system from different locations solves the challenge posed by high temperatures during midday at the farm. This advancement mitigates the need for farm workers to be physically present on-site and offers a solution to address the challenges presented by extreme heat conditions during certain times of the day. Through the practical operations conducted in the test plots, whether it be nutrient solution replenishment, pH adjustment, or water refill, it was observed that conventional operations took up a considerable amount of time. Specifically, in normal operations, it took up to 1 h per table for tasks to be completed. When considering the work for two tables, the total time required was 2 h each day. However, upon implementing the IoT system, the working time was significantly reduced to just 30 min per table, resulting in a total of 1 h for two tables each day. This indicates a time-saving of up to 50%. Hence, the IoT system has become an appealing option for farmers not only due to its safety features but also its time-saving advantages.

The relationship between parameters and plant growth in Chinese cabbage cultivation is shown in Table 4. The growth of Chinese cabbage from the experiments revealed the significant importance of pH control. In the conventional cultivation setup, the pH tended to increase notably, surpassing a level of 7.0 during the continuous period of weeks 2 to 4. This trend persisted despite weekly pH adjustments, causing plants to lose their ability to absorb nutrients efficiently. Most plants tend to thrive within a slightly acidic environment, with pH levels ranging from 5.5 to 7.0. Rapid pH shifts lead to plant stress and hinder optimal growth [22]. Comparing this to the IoT cultivation system, which maintains a consistent pH level through continuous monitoring and adjustment (every 5 s), results in healthier growth due to optimized nutrient absorption. Increasing electrical conductivity (EC) can impede nutrient absorption in plants by raising the osmotic pressure of nutrient solutions, rendering nutrients unusable and potentially releasing them into the environment, thus contributing to pollution. Conversely, low EC values can negatively impact plant health and productivity [23]. In general, conventional cultivation saw rapid decreases in EC during weeks 3 and 4 of Chinese cabbage growth, leading to suboptimal growth compared to IoT cultivation. The IoT system slowly decreased EC values over the fourth week, maintaining an environment conducive to healthy growth. A suitable temperature is pivotal for photosynthesis and respiration processes in plants. Temperatures exceeding 40 °C generally limit carbon assimilation during photosynthesis and can cause physiological stress [24]. Conversely, temperatures lower than 40 °C are considered optimal. Experiments showed that outdoor temperatures were 1–2 degrees Celsius higher than indoor temperatures. Inside both cultivation houses, the maximum temperature remained near 38 °C, as controlled by shade netting within the greenhouse to prevent excessive heat. Moreover, the water temperature was observed to be 1–2 °C lower than the air temperature, regulated by a water controller. The experiments revealed that the maximum water temperature was around 36 °C, which did not significantly affect the root growth of plants. As a result, both normal cultivation and IoT cultivation showed similar root growth. However, excessively high water temperatures can lead to decreased oxygen availability in water, potentially causing oxygen deficiency in the roots. Therefore, controlling water temperature appropriately is a crucial factor.

Table 4. Relationship between parameters and plant growth in Chinese cabbage cultivation.

Parameter	Relationship with Plant Growth	Notes
pH (6.0–6.5)	Optimal range for nutrient availability	Fluctuations in conventional system could harm growth.
EC (1.5–2.5 mS/cm)	Optimal range for nutrient concentration	Fluctuations in conventional system could affect growth.
Air Temperature	High temperatures can stress plants	Generally consistent throughout experiment.
Water Temperature	Generally consistent with air temperature	High temperatures can lead to water stress.
Humidity	Inverse relationship with temperature	High humidity can promote disease, low humidity can cause water stress.
Light Intensity	Essential for photosynthesis	Varies throughout the day, higher outdoors.

Research findings indicated that Chinese cabbage grown in the hydroponic smart farm exhibited better growth than those cultivated conventionally in hydroponics. The total fresh weight of Chinese cabbage in the IoT hydroponic system was 352.93 g plant^{-1}, whereas in the conventional hydroponic setup, it was 277.60 g plant^{-1}. This difference was considerably higher than the results of Choi et al. [25], who achieved a maximum of 319.00 g plant^{-1}, and Ducsay and Varga [26], who obtained a maximum of 247.20 g plant^{-1}.

This strengthens the argument for the effectiveness of the smart farm system in promoting superior growth. The IoT hydroponic cultivation showed a 27.14% increase in total fresh weight and a 48.90% increase in total dry weight, suggesting a significant improvement in overall plant biomass production. This could be attributed to factors like optimized nutrient delivery, precise control over environmental conditions (light, temperature, and humidity), and potential disease or pest reduction by the smart farm's automation. The findings also indicate improved vegetative growth parameters. The increase in plant height (11.14%), stem diameter (32.89%), leaf area (94.30%), leaf width (32.36%), and leaf length (38.12%) suggest a healthier plant with a potentially higher yield (Table 5).

Table 5. The growth comparison and quality assessment of Chinese cabbage plants grown in NFT-hydroponics with and without IoT systems, highlighting the significant differences observed between the two cultivation methods.

Parameter	Comparison	Result	Statistical Significance
Plant Height	IoT vs. Conventional	IoT plants taller, 11.14% elevation	$p < 0.05$
Stem Diameter	IoT vs. Conventional	IoT plants thicker, 32.89% increase	$p < 0.05$
Leaf Number	IoT vs. Conventional	No significant difference	$p > 0.05$
Leaf Width	IoT vs. Conventional	IoT plants wider, 32.36% increase	$p < 0.05$
Leaf Length	IoT vs. Conventional	IoT plants longer, 38.12% increase	$p < 0.05$
Leaf Area	IoT vs. Conventional	IoT plants larger, 94.30% increase	$p < 0.05$
Root Length	IoT vs. Conventional	IoT plants longer, 15.94% increase	$p < 0.05$
Shoot Fresh Weight	IoT vs. Conventional	IoT plants heavier, 28.09% increase	$p < 0.05$
Root Fresh Weight	IoT vs. Conventional	No significant difference	$p > 0.05$
Total Fresh Weight	IoT vs. Conventional	IoT plants heavier, 27.14% increase	$p < 0.05$
Shoot Dry Weight	IoT vs. Conventional	IoT plants heavier, 48.99% increase	$p < 0.05$
Root Dry Weight	IoT vs. Conventional	IoT plants heavier, 47.24% increase	$p < 0.05$
Total Dry Weight	IoT vs. Conventional	IoT plants heavier, 48.90% increase	$p < 0.05$
Nitrate Accumulation	IoT vs. Conventional	No significant difference, both safe	$p > 0.05$
Chlorophyll Content	IoT vs. Conventional	IoT plants higher chlorophyll, 22.73% increase	$p < 0.05$

The implementation of IoT reduced the harvesting time compared to conventional cultivation, from 42–45 days down to 39 days, while still achieving the same yield. Harvesting at day 42 was approximately 3–6 days earlier, resulting in savings on water, electricity, and fertilizer costs. When harvesting at day 42, the fresh weight of Chinese cabbage was 352.93 g plant^{-1} in the IoT system, compared to 277.60 g plant^{-1} in conventional cultivation. This represented a 27.14% increase in weight, equivalent to a 19.66 kg increase per table or an additional 688.10 Thai Baht per table (a greenhouse contains 4 tables, and each table has 261 plants). The calculation used a market price of 35 Thai Baht per kilogram.

Chlorophyll content in plant leaves affects photosynthesis efficiency and growth. This study compared the chlorophyll content of hydroponically cultivated Chinese cabbage to European Union (EU) standards, which dictate a maximum of 3500 mg kg^{-1} fw of nitrate accumulation for fresh vegetables [27,28]. Results indicated that conventional hydroponic cultivation accumulated 1199.50 milligrams per kilogram of nitrate, while IoT hydroponic cultivation accumulated 1233.50 milligrams per kilogram. Both of these values were below 50% of the EU standard. Furthermore, when compared to other cultivation methods in Thailand, such as hydroponics, organic farming, and soil-based cultivation, both IoT and conventional hydroponic cultivations had significantly lower nitrate accumulation, with IoT hydroponics achieving a 22.73% reduction.

In Thailand, there are no specific standards for nitrate accumulation in vegetables. Thus, this study compared the findings to the European Union regulations, which provides a clearer benchmark.

5. Conclusions

The study on the application of IoT technology in smart farming for Chinese cabbage grown hydroponically discovered various benefits. Compared to traditionally grown plants, those in the IoT-monitored system grew faster in terms of height, stem diameter, leaf size, and root length. In addition, the IoT group produced more biomass, with higher fresh and dry weights for shoots and roots. Furthermore, the study found that the IoT cabbages had greater photosynthetic activity, as seen by their higher chlorophyll content and greener leaves. Importantly, the study guaranteed the safety of the food by demonstrating that nitrate levels were below permissible limits in both groups.

IoT technology aids agriculture in three ways: through remote monitoring, automation, and real-time data collection. It minimizes labor expenses through remote management and automated chores, enables precise monitoring and control of growing conditions for maximum plant health, and eventually leads to enhanced yields and higher product quality.

Future research in IoT-based agriculture should concentrate on three main topics. To begin, analyzing these systems' long-term performance and maintenance requirements is critical to ensuring their sustainability and effectiveness over time. Second, determining the cost-effectiveness of IoT implementation is critical for broader acceptance, particularly among smaller farms. Finally, investigating the possibility of scaling up IoT solutions and smoothly combining them with other agricultural technology, such as precision farming tools, can help them reach their full potential and change the agricultural environment.

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