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Article

Design and develop an IoT automated nutrient control in a hydroponic system

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A B S T R A C T

Hydroponics farming is becoming increasingly popular due to its consistent ability to produce healthier plants in a controlled environment and nutrient solution. However, precise and frequent monitoring of the pH, temperature, and nutrient level is required in traditional hydroponic systems, which makes the labor monitoring process more complex and time-consuming. The aim of this study is to present the prototype of an automated nutrient control system that is applied in Nutrient Film Technique (NFT) hydroponic systems. The control system combines different sensors to monitor pH and EC levels continuously with the assistance of an Arduino Uno R3 microcontroller to process real-time monitoring data to adjust nutrient ratios dynamically. Meanwhile, the observation of lighting duration on indoor plant growth was recorded to justify the usage of indoor lighting for growing commercial crops. In this study, we used Dwarf Bak Choy (Brassica rapa chinensis) to evaluate the effects of various nutrient solution concentrations and lighting on plant growth.

1. Introduction

Hydroponic farming is becoming more popular in farming industries, and it is commonly integrated with sensors for remote monitoring of important nutrient solution parameters, such as pH and EC, which are critical for the growth of the targeted crop. This project aims to develop an automated nutrient control system to eliminate the need for labor-intensive manual intervention and provide long-term solutions to manage these variables in an NFT hydroponic system. By addressing the limitations of traditional hydroponics farming during the farmer's manual operations, such as managing large plant populations, nutritional inputs, and controlling NFT hydroponic environmental parameters. The proposed IoT device collects sensor data and transfers it to a cloud server for analysis and storage. The growing parameters of dwarf Bak Choy (Brassica rapa chinensis) will be used to verify the effectiveness of the proposed automated control system. The proposed approach aims to enhance the growing efficiency and reliability of the Bak Choy by observing the adjusted environmental and nutrition data. Compared with traditional soil farming, hydroponic farming has mitigated challenges of conventional farming, such as soil fertility and climate dependencies. However, it still faces issues in controlling precise pH and nutrient concentrations for promoting plant growth. Two common issues related to nutrient concentrations in hydroponic farming are insufficient nutrients and excessive concentrations. Insufficient nutrients can hinder the growth of the plant, in which targeted plant parts such as flowers, the plant body, or roots will not grow in time as expected. In contrast, excessive concentrations might induce stress and toxicity to plant growth, which is applied to sensitive crops such as tomatoes, spinach, wasabi, cucumbers, and lettuce [1]. From the result observations in Ref [2], for specific tomato species such as Rapsodie, moderate increased conductivity increased the maximum photosynthetic rate during the vegetative stage compared with low and high EC treatment. From the study conducted in Ref [3], the article found that excessive alkalinity can elevate substrate pH and reduce micronutrient availability to plants. The deployed automating systems for monitoring nutrient concentrations, pH levels, and water regulation offer significant benefits to growers, saving time and effort while providing accurate data during plant growth. The proposed automation enhances hydroponic systems by overcoming the disadvantages of manual nutrient management, thereby contributing to the cultivation of healthier crops. For many developing countries, an effective agricultural system is crucial for their economies to ensure targeted yield productivity. The traditional soil farming methods often require extensive resources such as land, water, and fertilizers, which lead to soil depletion and environmental challenges. Food production needs to double to meet the high demand from the increasing growth of the global population [4]. This necessitates exploring resilient food production solutions, especially amidst increasing climate instability. Hydroponics farming offers a promising solution to these challenges, minimizing land and water usage while maintaining high yields compared to traditional soil farming. From the recent trend, governments are increasingly adopting hydroponic farming in urban areas to enhance food accessibility. For example, Singapore has transformed flat house residential and commercial building rooftops into Sky farms, which leverage advanced hydroponic farming technologies to strengthen local food production.

Among hydroponic methods such as Wick System, Deep Water Culture, and Ebb & Flow, Nutrient Film Technique (NFT) stands out for its efficiency and common implementation. In NFT, a continuous circulated flow of shallow and oxygen-rich nutrient solution across the roots supports the growth of plants on racks. However, due to the cycling flow of the nutrient solution, monitoring and controlling water temperature, oxygen contents, pH levels, and EC become crucial for optimizing plant growth. Adjusting nutrient concentrations and pH levels can ensure targeted crops receive adequate nutrition, with verification of the EC sensors, which can indicate nutrient concentration levels necessary for plant health. This experimental methodology can help to propose appropriate adjustments for optimizing hydroponic yields and sustainability.

Deep knowledge of plant nutrition is crucial to justify the ratio of nutrients and lighting duration for effective automated system implementation. Meanwhile, integrating sensor technology for farming automation will help establish a proper system for analyzing crop-specific needs and environmental impacts. This project aims to provide insight into environmental impacts for plant growth by utilizing a proposed IoT monitoring system and developing an automated control system for controlling lighting and nutrient distribution. Deploying the automation prototype addresses the challenges of implementing precise nutrient management. The system will ensure controllable nutrient distribution during NFT hydroponics, which helps to fill current knowledge gaps and offer practical solutions to farmers, empowering them with valuable technological tools and insights.

2. Background literature

Researchers have made significant contributions to automation in hydroponics, particularly through adopting IoT technologies aimed at enhancing productivity, sustainability, and crop yields. IoT systems facilitate precise monitoring and regulation of critical environmental factors such as pH levels, fertilizer concentrations, humidity, and temperature in hydroponic setups. This capability enables more consistent control overgrowth conditions, potentially boosting crop yields while reducing labor demands. Several studies have explored the integration of IoT in hydroponic systems to optimize plant growth efficiency. For instance, Mapari [5] developed a vertical hydroponic farming system utilizing IoT for automated irrigation and real-time pH, TDS, temperature, and humidity monitoring. The system, controlled by a Node MCU microcontroller, transmits sensor data to a server and a mobile app via Wi-Fi. It notifies users of anomalies via email, showcasing its novel feature of automated irrigation management and remote monitoring capabilities. Similarly, Asawari et al. [6] proposed an automated hydroponic system leveraging IoT to collect real-time temperature, humidity, and pH data for optimal basil plant growth. Their ATMEGA2560 microcontroller-based system demonstrated a significant 58% increase in plant growth height over a 10-day period compared to traditional outdoor cultivation. In another approach, Sisyanyo et al. explored hydroponic smart farming using a cyber-physical-social system integrated with Telegram Messenger [7]. Their Raspberry Pi-based system monitored parameters like light intensity, room temperature, humidity, pH, nutrient temperature, and EC in real-time, enabling farmers to access instantaneous updates on plant conditions. In summary, these studies highlight the recent trend of IoT implementation for advancing hydroponic farming, adapting in practical usage through enhanced automation, real-time monitoring, and improvement of agricultural outcomes. In Ref [8], the author suggested that the integration of IoT with the automated hydroponic systems offers numerous advantages and poses certain limitations, such as the setup cost, which can be unaffordable for small-scale farming, and reliable internet connections are needed to ensure proper monitoring and control in place. In addition, the integration of traditional farming with technology will cause more technological dependencies, which increase vulnerability to technical failures and potentially affect crop yields. Specialized knowledge and training may pose challenges for some users in system operation and maintenance. Moreover, indoor hydroponic farming demands significant energy resources for 24-hour operation, which could be restricted in areas with limited or costly energy supplies.

Sisyanto et al. [7] mentioned several limitations of IoT hydroponic farming, including the accuracy of nutrient monitoring, which could be potentially compromised due to the installation of multiple sensors for nutrient monitoring. The fault of the pH or EC sensors could affect crop growth. Additionally, the monthly subscribed internet connection requirement for IoT systems could be impractical or costly in certain regions or applications for continuous monitoring purposes. The study doesn't integrate output relays for electronics devices like humidifiers to regulate moisture levels. It excludes camera modules for visual plant growth monitoring, which could offer valuable insights into plant growth monitoring. The EC sensor measurement is crucial in hydroponics implementation, as it indicates the concentration of electrolytes in nutrient solutions [9]. These solutions, typically divided into A and B formulations, contain essential macronutrients and micronutrients necessary for plant growth. Maintaining optimal nutrient levels is crucial; insufficient nutrients can lead to plant diseases, while excessive levels can foster algae and bacterial growth detrimental to plants [10]. Ding et al. conducted studies on Bak Choy, determining that an EC range of 1.8 to 2.4 in greenhouse conditions resulted in higher photosynthesis rates, productivity, and superior yield compared to other treatments [9]. The pH levels in hydroponic systems, affecting hydrogen ion concentrations, are adjustable using specific chemicals like phosphoric acid for lowering pH and potassium bicarbonate for raising it [11]. Optimal pH typically falls within the range of 5.5 to 6.5, as highlighted in various studies [12]. Maintaining a slightly acidic pH is preferred to prevent the precipitation of essential nutrients like Fe, Mn, Ca, and Mg, which occurs at higher pH levels [13]. Higher pH levels also reduce the availability of potassium (K) and phosphorus (P) in nutrient solutions.

Light, consisting of seven different colors, profoundly influences plant growth along with water, air, space, and nutrients. Kui et al. emphasize the roles of red and blue light in promoting callus production, assimilate movement, biomass accumulation, phototropism regulation, chloroplast migration, stomatal opening, leaf expansion, and photosynthetic protection [14]. Their research demonstrated that lettuce illuminated with RGB (6:2:2) LED light at 150 $\mu mol.m^{-2} \cdot s^{-1}$ PPFD produced healthier, higher-quality yields compared to plants under singular or mixed blue and red-light conditions. Similar studies by Li et al. [15] corroborated these findings. Additionally, Mickens et al. studied red Bak Choy growth under various LED lighting ratios [16], concluding that a 3:1 ratio of red to blue LEDs yielded the highest biomass and nutrient content over 28 days of growth.

3. Methodology

The prototype's design involves two key aspects: hardware and software. The hardware design involves installing the NFT hydroponic system and selecting appropriate electrical components. On the other hand, the software design focuses on developing an Arduino code algorithm to enable automated control of the system. Both aspects are critical in ensuring the project's successful implementation and operation. The NFT hydroponic system is designed with three shelves, each featuring four rectangular PVC pipes dedicated to plant cultivation. Each PVC pipe is equipped with five precisely cut planting holes, totaling 20 holes per shelf and 60 across the entire system. The dimensions of the rack measure 1.83 meters in length, 92.5 cm in width, and 92.5 cm in height.

To ensure optimal root oxygenation, the planting holes are precisely 42mm in diameter, accommodating net pots that suspend the upper roots above the nutrient solution. The proposed design promotes efficient nutrient uptake and oxygen absorption from the surrounding air, which is crucial for plant growth. For artificial indoor lighting, 14W LED tube lights were installed, emitting red, blue, and white light in a ratio of 3:2:1, which enhances photosynthesis and supports robust plant development by referring to the approach in [17]. The proposed hydroponic system shown in Figure 1 includes three separate 20-liter water reservoir tanks, one for each shelf level, allowing separate nutrient solution management and experimentation with different growing conditions. Each reservoir is equipped with a motor pump to deliver mixed nutrient water to the targeted plants on shelves. Additionally, air pumps with air stones in each reservoir were installed to enhance oxygen content within the nutrient solution, promoting plant yield and health. The well-integrated sensor module for the NFT hydroponic system includes several essential parts. The integrated system included pH sensors, which measure solution acidity or alkalinity based on potential differences detected by the pH meter probe, with proper room temperature control ensuring precise readings.

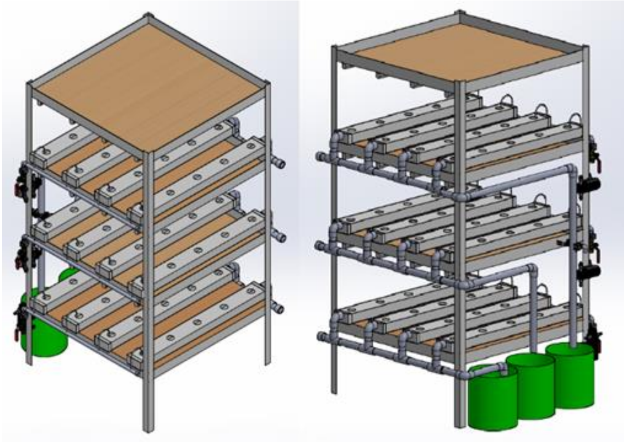

Figure 1. Front and back views of the NFT hydroponic setup

Moreover, an EC sensor supports Arduino integration, measuring the nutrition concentration in the flowing nutrient solution. To monitor reservoir water temperature, we deployed the DS18B20 water temperature sensor, known for its waterproof design and high accuracy (±0.5^{0}C). These sensors can be embedded into an Arduino Mega, and the microcontroller will act as the central processing unit to receive data and control nutrient distribution. For IoT monitoring, data visualization, and management, ThingSpeak was utilized as a cloud platform that enables real-time streaming, data storage, and visualization of sensor data. This solution offers robust integration with Arduino for monitoring hydroponic parameters remotely. The integrated Arduino Mega system consists of an ESP8266 Wi-Fi module, which can provide internet connectivity to support IoT applications. The actuator module will control electronics components such as a relay for triggering pumps to adjust the nutrient solution ratio in reservoirs. Meanwhile, the EC levels can be managed with common nutrient solutions A and B from Lotus Farm Agritech. The three-level NFT hydroponic rack was equipped with 14W LED lights, as mentioned earlier. The experiment was conducted in controlled environmental conditions with air conditioning to test the growth responses of Bak Choy under different lighting durations and nutrition ratio setups. The proposed setup method offers various advantages, including real-time remote monitoring via sensors, streamlined data management with ThingSpeak, and precise control through the actuator module. However, due to the centralized HVAC, environmental temperature control is limited. The proposed experiment will evaluate sensor accuracy, IoT integration, standardized experimental conditions, and the impact of the environmental conditions on plant growth. The proposed control system in Figure 2 is designed to align with its objective of enhancing plant growth through IoT monitoring and controlling key parameters in the nutrient solution. Multiple sensors, such as water flow rate, EC, temperature, humidity, and pH, are integrated into the embedded electronic system. These sensors were attached to an Arduino Mega controller, which enables real-time monitoring and control. DHT11 was installed to capture room temperature and humidity, YF-S201 is used to measure the water flow rate, and DS18B20 waterproof probes were used to measure the water temperature.

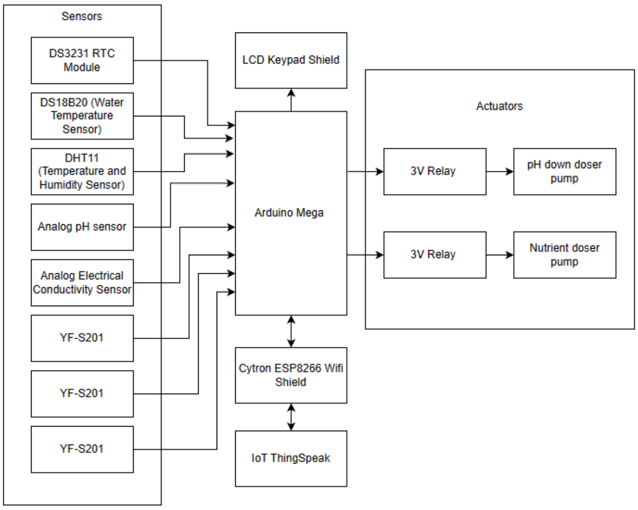

Figure 2. Block diagram of an automated system

This environmental data is crucial for monitoring environmental conditions during plant growth. The data collected from these sensors will be uploaded to the online server via ThingSpeak for data aggregation, visualization, and analysis across six dedicated channels for different lighting and nutrient mix growing monitoring purposes. A part of the approach of monitoring and regulating the nutrient solution will be controlling pH levels in the nutrient solution to maintain between 5.5 and 6.5, which is recommended in Ref [12]. The system will trigger a pH down dozer pump using 30% concentrated phosphoric acid to lower the nutrient solution pH back into the optimal range if the pH level exceeds 6.5. This approach controls precise pH control for nutrient availability and plant health. The analog EC sensor is employed to monitor the concentration of electrolytes in the nutrient solution for assessing nutrient concentrations. The proposed automated system manages three water reservoir tanks, which are tested for optimal EC values through controlled mixed A and B solutions as needed. Water temperature fluctuations will impact pH and EC values. Therefore, the water temperature will be monitored and calibrated using data from the DS19B20 temperature probe every three days, following the manufacturer's guidelines for better pH and EC measurement accuracy. Due to the laboratory sensors being adopted for the automated system implementation, the system requires adjustment to address sensor immersion limitations and ensure the reliability of ongoing operation. The calibration routines were set to ensure the sensor system can maintain accurate parameter readings, which ensure the targeted commitment to optimizing hydroponic conditions for robust plant growth and health. As part of the system design, the automated system will regulate light duration parameters within the pre-experimental setup, as shown in Figure 3. The Arduino Mega microcontroller is functioning as the principal controller to facilitate precise time management for controlling LED tube lights based on the predetermined timer settings. For time duration monitoring, the system employs a DS3231 RTC time stamping module, which will help to enable the activation and deactivation of a 5V relay responsible for managing the lighting system's operation. In addition, the RTC module will display the current time on an LCD interface connected to the Arduino Mega. This feature will provide real-time feedback to users and ensure that lighting schedules are maintained accurately according to the specified setup. With the integration of these components, the automated system can improve the efficiency of light regulation in the hydroponic system, which can consistently support the optimal growth and verification of various lighting durations. There are several experimental setups that were conducted to compare and verify the performance of different hydroponic systems, which mainly focus on plant growth index parameters such as height and number of leaves over the growth period. The experiments used seeds of the dwarf Bak Choy (Brassica rapa chinensis) cultivar, germinated uniformly under controlled conditions for 10 days. Afterward, 36 seedlings with consistently sized initial leaves were carefully chosen and transplanted into the setup.

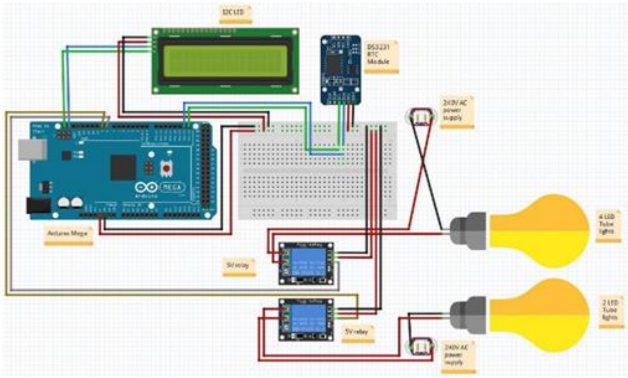

Figure 3. Circuit diagram of a light control system

The hydroponic system consisted of three shelves and was divided into six sections as shown in Figure 4, with two sections per shelf separated by a cardboard divider. Each section accommodated six sets of dwarf Bak Choy plants. The left side of the shelves was exposed to a 12-hour light cycle with alternating 4-hour light and 4-hour dark periods, while the right side experienced continuous 24-hour lighting. All plants were subjected to identical environmental conditions within the same growth room. From Day 7 to Day 25 of the experiment, leaf number and plant height measurements were taken every three days.
Figure 5 shows that three different treatments were applied to the racks:

i) Level 1 rack underwent an EC of 0.8 mS/cm for the first eight days, followed by 1.7 mS/cm for the subsequent 18 days.
ii) Level 2 rack maintained a constant EC of 1.6 mS/cm throughout the 25-day experiment.
iii) Level 3 rack started with an initial EC of 2.1 mS/cm for the first eight days, followed by 1.1 mS/cm for the remaining 18 days.

On the 8th day of observation, adjustments were made to the water reservoirs of the Level 3 rack to address a sudden drop in EC value. Water pumps operated continuously, and pH levels were maintained within the range of pH 5.5 – 6.5 throughout the experiment. All data were collected concurrently to ensure consistency and comparability across different growth conditions.

Figure 4. Three-level rack divided into six sections for each group of dwarf Bak Choy

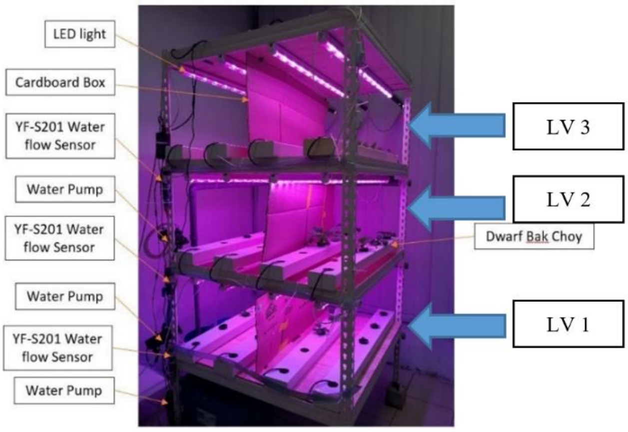

Figure 5. NFT hydroponic setup

4. Results and discussion

The growth of dwarf Bak Choy was thoroughly assessed using plant height and leaf count as key parameters, with significant differences observed across different lighting settings. On the Level 1 rack, plants subjected to 12-hour LED lighting showed average heights ranging from 1.46 cm to 2.48 cm over 25 days, while those under 24-hour lighting exhibited growth ranging from 3.23 cm to 5.4 cm. Similarly, on the Level 2 rack, plants under 12-hour lighting grew from 1.54 cm to 3.12 cm, whereas those under 24-hour lighting grew from 4.37 cm to 8.23 cm. At Level 3, plants under 12-hour lighting grew from 1.34 cm to 3.02 cm, compared to 4.25 cm to 6.68 cm under 24-hour lighting. Leaf count variations were minor initially but became significant from day 16 onwards, with plants under 24-hour lighting generally showing greater leaf production by day 25. Specifically, plants on 24-hour lighting had an average leaf count of 10 to 12 across all levels, while those under 12-hour lighting averaged 7 to 9 leaves as shown in Figure 6.

The automated control system effectively managed pH and EC values throughout the experiment, as depicted in Figure 7. Each rack maintained different EC levels: Level 1 started at 0.8 mS/cm for eight days, then increased to 1.7 mS/cm; Level 2 maintained a steady 1.6 mS/cm; and Level 3 began at 2.1 mS/cm for eight days, then reduced to 1.1 mS/cm. The system generally maintained EC within the specified range, although occasional pH drops below 5.5 indicated overuse of the pH down doser solution. To address this, adjustments in dosing frequency are recommended, possibly incorporating a pH up solution for more balanced pH management. Overall, while demonstrating effective regulation of nutrient solution parameters, the system requires fine-tuning to optimize pH control and ensure consistent performance across varied experimental conditions.

When comparing the findings of this study to other relevant research in automated control systems for nutrient distribution in hydroponics, it becomes evident that the proposed system demonstrates promising results. In a study by Prasetia et al. [18] focusing on IoT-based grow light automation, they found that dwarf Bak Choy grown under LED lights showed superior performance in terms of fresh weight, number of leaves, and plant height compared to those grown under sunlight. Especially on the 30th day, the result showed the improvement of plant growth, which under LED lights averaged 23.6 grams, 11.2 leaves, and 18.1 cm in height, compared to that under sunlight, which averaged 20.2 grams, 9.3 leaves, and 17.1cm. From experimental observation, this underscores the positive impact of an automated hydroponic system on plant growth and its productivity through the controlled environment.

The result agreed with the LED illumination and IoT technology with Zigbee in Ref [19], which explored a smart hydroponic system implementation. The article's findings discovered improvements over traditional farming methods with a 17.2% increase in leaf yield, 29.85% taller plants, and 14.55% higher in terms of produced weight, which means that harvesting can be earlier by two weeks compared to conventional farming. The outcomes showed that the duration of LED lighting can promote plant growth, yield, and efficiency in agriculture.

The data collected from the present study aligns with the findings from previous studies, which demonstrate significant differences in plant height and leaf count across different lighting duration settings. Moreover, the automated system effectively maintained pH and EC within optimal ranges, which offers optimized growth conditions. With the controlled environment and nutrient management, the automated system not only supports increased yields but also promotes sustainable resource use. For different nutrient settings, the result showed that there is no significant difference between growth in Level 1,2, and 3 racks with controlled EC settings.

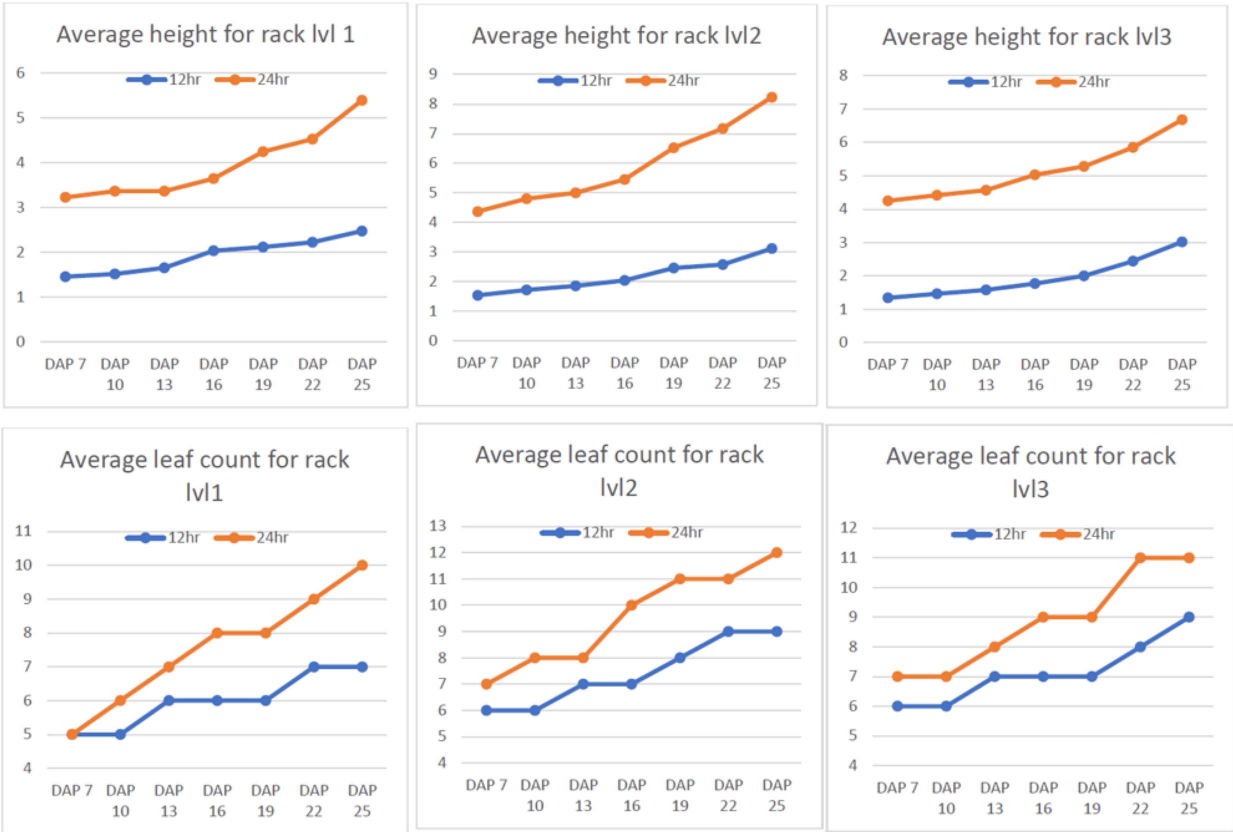

Figure 6. Graphical analysis of plant height and number of leaves of different growth conditions from DAP (Day After Planting) 7 to 25

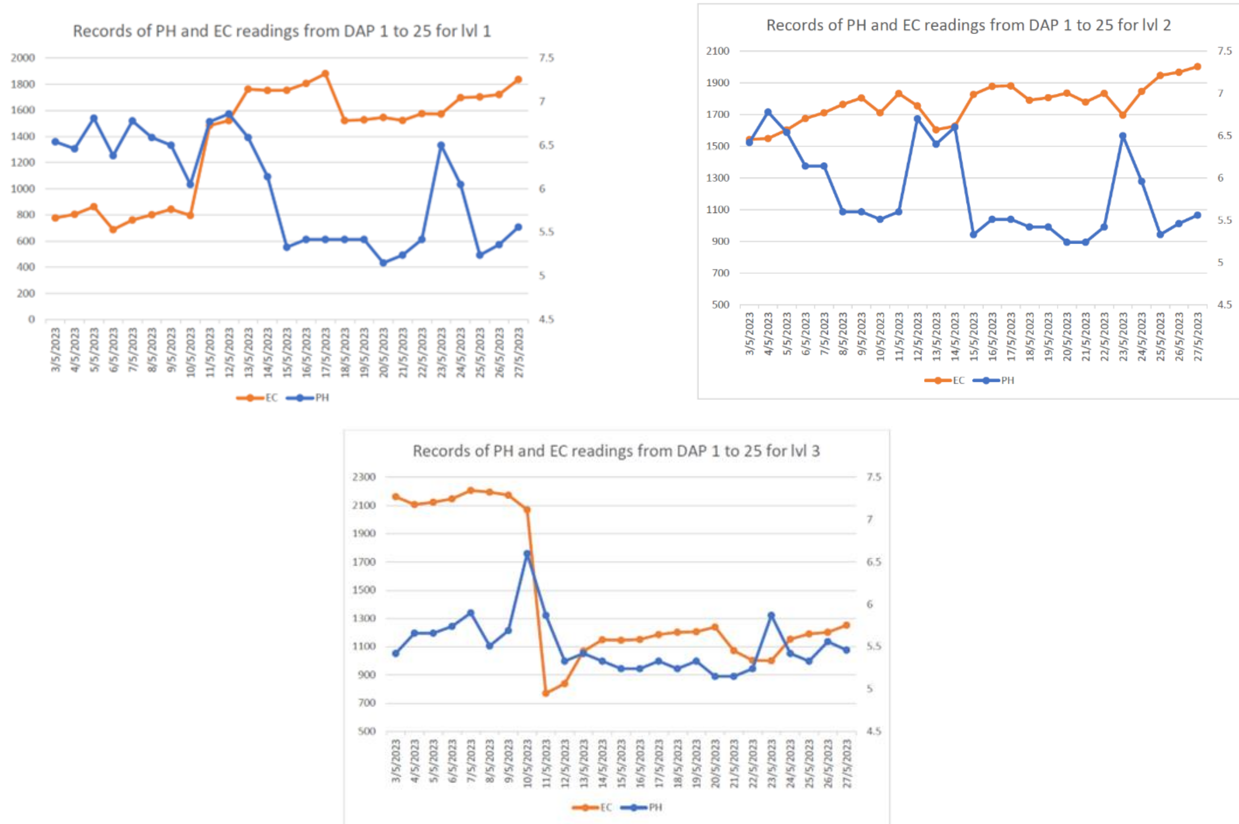

Figure 7. Records of pH and EC readings from DAP 1 to 25 for three different levels

It is observed that a high nutrient setting at the beginning of the growth stage will promote the growth of the Bak Choy, as shown in Figure 6, with levels 2 and 3 racks set to have more nutrients mixed in the NFT system compared to the level 1 rack. Results observed from the level 3 rack showed that high conductivity values in nutrient solutions do not promote significant plant growth. The result agrees with the observation in [2], in which moderate EC treatment increased the conductivity, which in turn increased the maximum photosynthetic rate compared to high and low EC treatments. From the experimental result, this study contributes compelling evidence for the effectiveness of automated control systems in hydroponic farming. With the integration of IoT systems and sensor monitoring, the proposed prototype offers pathways to enhance agricultural productivity and sustainability. The findings underscore the potential for future improvements in hydroponics practices for different target crops, which emphasizes the role of technology in driving agricultural innovation and addressing sustainable development goals regarding food security issues. Several technological aspects were previously developed by the authors to monitor the growth rate of the plants and their relevant parameters [20- 23].

5. Conclusions

This paper demonstrated the impact of the different lightning settings on the Bak Choy growth through an automated IoT control system for nutrient and pH control in NFT hydroponic systems. The findings indicated that plants exposed to 24 hours of lighting showed a significant increase in plant growth indices, such as height and leaves, compared to those under 12 hours of lighting duration, with variations in nutrition distributed across different rack levels. The automated system successfully maintained the pH and EC levels within the suggested ranges through minor fluctuations in pH, which emphasized the need for fine-tuning in dosing adjustments or earlier predictions in the pH rising trend. The experimental results aligned with the previous studies, which support the moderate increase of EC value and will help promote higher plant yields, improved growth rates, and efficient resource utilization. With the integration of IoT monitoring and control, the study suggests the potential of automation implementation in enhancing hydroponic farming approaches in terms of efficiency. The future work of this project should focus on refining pH stability, optimizing nutrient dosing strategies, and expanding the automated system's adaptability to diverse targeted plants. In the past, the team had developed various technological solutions for supporting and monitoring plant growth. Eventually, these automation implementations contribute to sustainable agricultural practices, supporting the Sustainable Development Goals and innovation in smart farming technologies.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

Abbreviations

DHT22	Temperature & Humidity Sensor
DS18B20	Water Temperature Sensor
EC	Electrical Conductivity
HAVC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
MCU	Micro-Controller Unit
NFT	Nutrient Film Technique
pH	Potential of Hydrogen
PVC	Polyvinyl Chloride
TDS	Total Dissolved Solids
PPM	Parts Per Million
PPFD	Photosynthetic Photon Flux Density
RTC	Real-Time Clock

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