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INTEGRATION OF IoT TECHNOLOGY IN HYDROPONIC SYSTEMS FOR ENHANCED EFFICIENCY AND PRODUCTIVITY IN SMALL-SCALE FARMING

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As global population growth and decreasing arable land create a demand for increased food production, hydroponic farming is gaining popularity due to its numerous advantages over traditional agriculture. However, high costs and limited accessibility of commercial hydroponic systems remain a challenge for small-scale farmers, especially in developing countries. This research paper presents a novel hydroponic system that leverages the Internet of Things (IoT) technology to enhance small-scale agriculture through the monitoring of crucial parameters such as electrical conductivity (EC), pH levels, temperature, and humidity. The system integrates wireless sensor nodes that send data to a central control unit for real-time monitoring and adjustments. A comparative analysis between a semi-automatic control system and a conventional control system demonstrated that the semi-automatic system resulted in enhanced plant growth, especially in Red Cos lettuce, leading to increased yields. The research emphasises the significant potential of intelligent hydroponic systems in revolutionising conventional farming techniques and providing valuable support to small-scale farmers.

Keywords: hydroponic farming; real-time monitoring; nutrient management; sustainable agriculture

By 2050, the global population is expected to grow to 9.7 billion of people. At the same time, it is anticipated that a half of world's arable land will be useless for farming in the near future. Because of this, the amount of food that may be produced must be increased by 110%. According to the United Nations (UN), several nations, particularly in Africa, are now experiencing a food crisis. It is predicted that the food crisis would persist until 2050 if the demand is not fulfilled (Gashgari et al., 2018). This scenario has spurred interest in indoor farming, particularly hydroponics, which offers numerous advantages over traditional agriculture, such as faster growth rates, reduced space requirements, and independence from seasonal changes. Hydroponics involves growing plants without soil, using mineral nutrient solutions dissolved in water to provide essential nutrients (Baras, 2018; Modu et al., 2020).

The primary components of a hydroponic system include a growing space, a reservoir for the nutrient solution, and mechanisms to maintain optimal levels of oxygenation, salinity, pH, and EC. Additional factors such as ambient temperature, nutritional solution temperature, photoperiod, and air humidity also play crucial roles in system's success (Gupta, 2004). It is possible to develop any hydroponic system through modification. Seven different types of hydroponic methods exist: Wick, Deep Water Culture (DWC) (Butcher et al., 2017; Wootton-Beard, 2019), Ebb and Flow (Sharma et al., 2018), Drip (recovery or non-recovery), Nutrient Film Technique (NFT), Aeroponics (Alkhalidi et al., 2019), and Fogponics.

Hydroponic farming, which is an alternative to traditional agriculture, has been gaining significant attention in recent years due to the advantages it offers. In literature, numerous hydroponic farming systems utilising IoT technologies have been designed and implemented. These systems are designed to measure and regulate various parameters, including temperature, pH, water level, light intensity, and nutrient concentration. Communication between devices in the system and the server is accomplished through a range of technologies, such as Ethernet, Wi-Fi, GPRS, satellite radio, and publish-subscribe middleware (Supriyanto and Fathurrahmani, 2019; Collado et al., 2021; Khudoyberdiev et al., 2020; Sihombing et al., 2018; Tatas et al., 2021, 2022; Vidhya et Valarmathi, 2018).

Kour et al. (2022) designed a smart hydroponic system for saffron cultivation using the nutrient film technique and renewable sources of energy. They conducted a comparative analysis of six hydroponic approaches to optimise the system's performance. Similarly, Siregar et al. (2016) aimed to increase the energy efficiency of hydroponic systems by automating the system's parameters such as temperature, pH, and water level. They also used solar energy as a source of electricity. Likewise, Hidayanti et al. (2020) designed a hydroponic system focusing on growth characteristics such as pH, temperature, liquid level, and light intensity, which are monitored using various monitoring technologies.

Moreover, Boonnam et al. (2017) integrated IoT and a wireless sensor network to design a hydroponic system that controls various components such as light,

humidity, and temperature. The data collected by sensors is continuously transmitted to the cloud for storage and future use. Furthermore, Ruengittinun et al. (2017) employed IoT devices to monitor humidity, nutrient solution, ambient temperature, pH, and EC in a hydroponic farming environment. The system uses a cloud-based IoT for managing and monitoring hydroponic systems using publish-subscribe middleware and MQTT protocol.

Several hydroponic systems have been designed to enable farmers to remotely control and monitor the various aspects of plant growth using IoT technologies. For example, Ullah et al. (2019) presented an IoT system that monitors and controls all the parameters of a hydroponic system via a mobile application, including water level, pH, humidity, and temperature. An alert will be sent to a farmer through SMS if the water level in the reservoir drops below a certain threshold. Through a smartphone application, the farmer can manage the water supply and fill the reservoir. Similarly, Peuchpanngarm et al. (2016) developed a sensor-based smartphone application that can be installed by the user. The application employs a variety of sensors, including those for water temperature, air temperature and humidity, and light intensity, to enable autonomous environmental control in hydroponics. Additionally, hydroponic farming comprises planning, maintenance, and the documentation of harvest data to satisfy planting requirements. Chuah et al. (2019) presented a cyber-physical system (CPS) that can offer a framework for farmers to remotely control and monitor the numerous aspects affecting plant development. The goal is to incorporate CPS into a vertical farming system by creating an Android-based remote monitoring and control system based on CPS to achieve proper plantation system output using Internet-connected Arduino ESP32 and sensors.

Various optimisation approaches have been proposed to effectively regulate the parameters of hydroponic environments while minimising energy costs (Alipio et al., 2019; Ruscio et al., 2019). For instance, Yolanda et al. (2018) suggested a new optimisation approach through establishing a working level and operational time for actuators, which allows for optimum energy and resource utilisation in the hydroponic system. They created a fuzzy-logic-based optimisation technique with an objective function for controlling humidity and water levels optimally, which may aid in precise monitoring for sustainable crop production.

The primary goal of this paper is to develop an economically viable and intelligent hydroponic system tailored to the needs of small-scale farmers, particularly in regions like Thailand. This system aims to reduce the complexity and costs associated with commercial hydroponic systems while ensuring effective management of nutrient levels. The paper presents several significant contributions to the field of smart hydroponic systems, particularly aimed at enhancing accessibility and efficiency for small-scale farmers. Firstly, it introduces a low-cost, intelligent hydroponic system that leverages the IoT technology to provide real-time monitoring and control of plant parameters through a user-friendly dashboard. This system includes a portable wireless solute meter capable of semi-automatically measuring of EC and pH levels, which are critical for optimal plant growth. Secondly, the study details the development of an integrated control unit equipped with a compact processing device that precisely dispenses water and nutrient solutions based on EC and pH data acquired from an MQTT broker. This ensures that nutrient delivery and environmental conditions are optimised, fostering healthier and more vigorous plant development. Overall, the paper provides a comprehensive solution that integrates cost-effective technology with practical applications, making it a valuable contribution to the advancement of sustainable and efficient hydroponic farming practices.

Material and methods

System design and development

The methodology employed in this study is centred on the development and execution of a cost-effective, hydroponic system specifically crafted to improve the accessibility and effectiveness of hydroponic agriculture for individuals engaged in small-scale farming activities. To observe the hydroponic crop farming process among local farmers in Thailand, a survey revealed that farmers commonly use small plastic-roofed net houses and employ the Dynamic Root Floating Technique (DRFT) to cultivate various crops such as kale, lettuce, and green oak. The DRFT operates by fluctuating the nutrient solution level, thereby creating a dual-zone root environment. In this system, roots are partially submerged in a nutrient solution: the lower part of roots absorbs nutrients, while the upper part remains

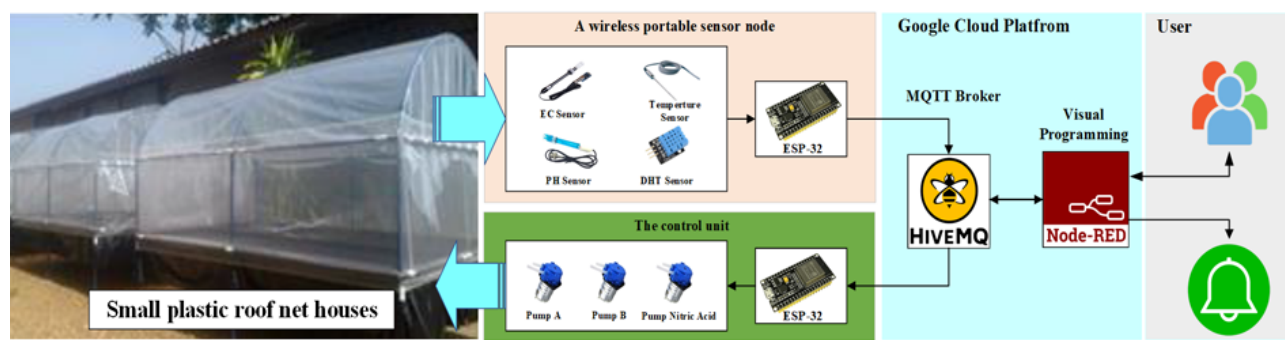


Fig. 1 Design of low-cost hydroponic system

exposed to air for oxygen intake. A pump fills the container with the nutrient solution to a certain depth, after which the solution drains back into a reservoir for reuse. The DRFT is particularly suitable for tropical and subtropical climates due to its ability to maintain a constant temperature. This is critical because warm water holds less dissolved oxygen, and the DRFT addresses this issue by keeping the upper roots exposed to air. Consequently, this study utilised the classical DRFT for its execution and experimentation.

In order to create a cost-effective hydroponic system, it is divided into two main components, as illustrated in Fig. 1. The initial component is the control unit, and the second component consists of sensor nodes. The control unit operates by utilising an ESP32 board as its core processing unit, which is responsible for receiving and processing data transmitted from sensor nodes to effectively manage and regulate the levels of EC and pH present within the hydroponic setting. Moreover, this unit is equipped with motor drives that can adjust the speed of peristaltic pumps, thereby facilitating precise control over the distribution of water, plant nutrient solutions, as well as acid, thereby guaranteeing that each individual plant within the system receives the necessary and appropriate quantity of essential nutrients for its optimal growth and development.

The block diagram of the system architecture consists of two parts, as shown in Fig. 2a–b. The wireless and portable sensor node has been developed to semi-automatically measure EC, pH, humidity, and temperature in any specify location within the hydroponic arrangement, thereby enhancing the effectiveness and convenience of data collection. The sensor node consists of an EC meter from DF Robot model DFR0300-v2, pH meter from DF Robot model SEN0161, DHT11 humidity and temperature sensor, and DS18B20 water temperature sensor.

These nodes assume a pivotal role in the comprehensive operation of the system by facilitating the real-time collection of data, a procedure further improved as the microcontroller interprets this data to execute precise modifications to the nutrient solution and environmental factors, ensuring the most favourable conditions for plant

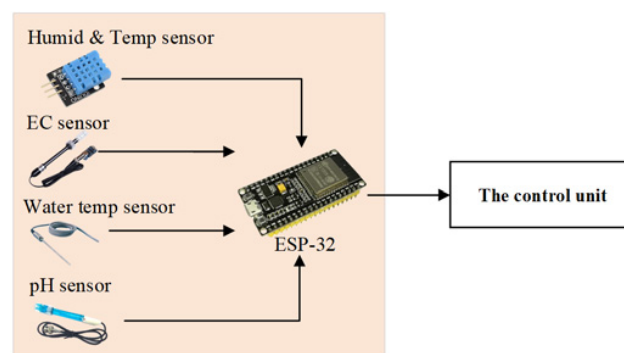


Fig. 2b Overall system architecture block diagram – node sensors

development. The data acquired via these sensor nodes is subsequently displayed visually on an intuitively crafted dashboard, established utilising Node-RED, providing an elaborate overview of the operational status and efficiency of the hydroponic system. Furthermore, this dashboard is furnished with functionalities empowering the system to generate proactive notifications for the user, guaranteeing timely updates and alerts concerning any essential actions or modifications that must be undertaken.

The study utilised a variety of data to evaluate the effectiveness of the hydroponic system. The key parameters measured included EC, pH levels, temperature, and humidity, both in the water and the air. These parameters were monitored using sensor nodes equipped with ESP32 boards, which published the data to the system controller via the MQTT protocol. Data collection was conducted in a real-world hydroponic setup, ensuring system's ability to accurately monitor and control these critical parameters.

Economic efficiency

To comprehensively evaluate the economic efficiency of the proposed semi-automatic control system for hydroponic farming, a detailed cost-benefit analysis was conducted. This analysis encompassed initial investment costs, operating costs, and the benefits derived from system

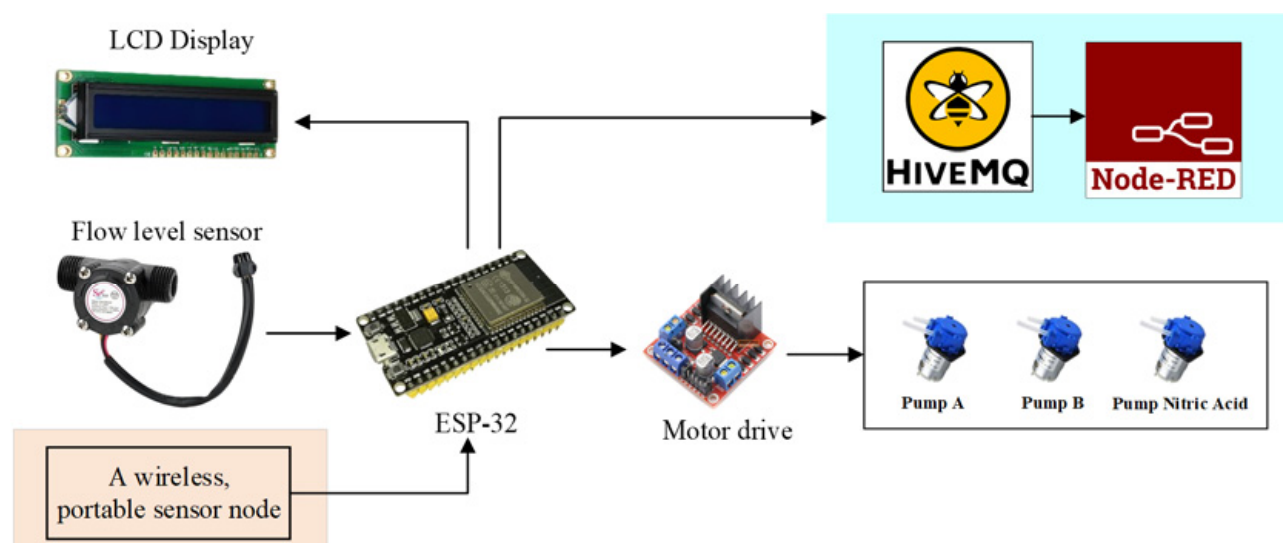


Fig. 2a Overall system architecture block diagram – the control unit

implementation. The following steps were incorporated into the evaluation:

1. Initial investment costs:
 - hardware costs: expenses incurred for node sensors, control units, and other necessary hardware components;
 - software development costs: including costs associated with the development of the IoT framework, programming, and integration;
 - installation costs: including costs related to setting up the system on the farm, including labour and any additional infrastructure requirements.
2. Operating costs:
 - maintenance costs: ongoing expenses for maintaining the hardware and software components of the system;
 - labour costs: the reduction in labour costs due to system and comparing it with current labour expenses.
3. Benefits:
 - yield improvement: the increase in crop yield due to optimised nutrient and environmental management;
 - time savings: the reduction in time spent on monitoring and adjusting the hydroponic system manually.

Experimental design and treatments

The experiment was designed as a true experimental research study to compare the growth results of Red Cos lettuce in the hydroponic system. The study involved an experimental group and a control group, with measurements taken after the experiment. The experimental group utilised a DRFT hydroponic plant system with controlled variables like pH and solution conductivity, along with notifications for pump operation and measurement time. On the other hand, the control group used a regular DRFT hydroponic system without a control system.

Maintaining optimal EC levels, pH balance, and a specific planting period are crucial for effectively managing the growth of Red Cos lettuce in hydroponic greenhouses. The experiment involved growing Red Cos vegetable seeds into seedlings over 10–15 days before transplanting them into separate hydroponic greenhouses. The plants were

divided into experimental and control groups, spaced 15 cm apart, and data was collected every three days from both groups. The optimal conditions for controlling the growth of Red Cos lettuce were found to be an EC of 1.0–1.8 mS·cm⁻¹ pH of 5.8–6.0, and a planting period of 45–60 days. The detailed procedures followed in the experiment ensured accurate data collection and comparison between the experimental and control groups.

Results and discussion

Performance of sensors and control system

In the experiment, the EC and pH values were compared between a semi-automatic control system and a normal control system. The EC of the water used in the system was initially measured at 2.1 mS·cm⁻¹. The results of the experiment showed that the semi-automatic control system was able to measure the EC and pH values similarly to the normal control system. EC was found to be controllable within the range of 1.0–1.8 mS·cm⁻¹, while pH was within the range of 5.8–6.0, as shown in Table 1. The results derived from this experiment affirm that the semi-automatic control system adeptly managed the EC and pH values, ensuring their sustained alignment within the requisite ranges for hydroponic Red Cos lettuce cultivation.

Dashboard monitoring and notification

Implementing a dashboard monitoring and notification system plays a vital role in efficiently controlling hydroponic crop operations. It is of utmost importance to have a well-structured dashboard powered by visual programming through Node-RED, as this enables the attainment of real-time monitoring capabilities. This dashboard not only serves the purpose of providing valuable insights into various operational statuses but also takes a proactive approach by communicating notifications to users in a timely manner.

The design of the dashboard window holds significant importance due to its role in presenting the critical status value, as shown in Fig. 3, including temperature, humidity, EC, pH levels, and water flow rates. By utilising gauges and graphical representations, the visibility of essential metrics is enhanced, thereby enabling users

Table 1 Electrical conductivity and pH values in semi-automatic vs normal control system

Day	Semi-automatic control system								Normal control system							
	EC (mS·cm ⁻¹)				pH				EC (mS·cm ⁻¹)				pH			
	min	max	mean	SD	min	max	mean	SD	min	max	mean	SD	min	max	mean	SD
15	3.5	4.1	3.78	0.23	5.3	5.9	5.7	0.24	3.4	4.0	3.74	0.25	5.3	6.1	5.74	0.30
18	3.5	4.0	3.74	0.18	5.4	5.9	5.64	0.24	3.4	4.2	3.68	0.28	5.4	6.3	5.72	0.38
21	3.4	4.0	3.68	0.24	5.6	5.9	5.84	0.13	3.3	4.0	3.66	0.28	5.6	6.1	5.88	0.18
24	3.6	4.3	3.82	0.29	5.5	5.9	5.78	0.18	3.4	4.1	3.68	0.23	5.5	6.0	5.8	0.20
27	3.7	4.0	3.8	0.14	5.6	5.9	5.82	0.13	3.5	4.1	3.72	0.22	5.6	6.2	5.88	0.22
30	3.5	4.1	3.78	0.22	5.4	5.9	5.76	0.22	3.4	4.1	3.66	0.26	5.4	6.2	5.82	0.29
33	3.6	4.1	3.82	0.22	5.5	5.9	5.74	0.22	3.3	3.9	3.56	0.22	5.5	6.2	5.8	0.30

SD – standard deviation

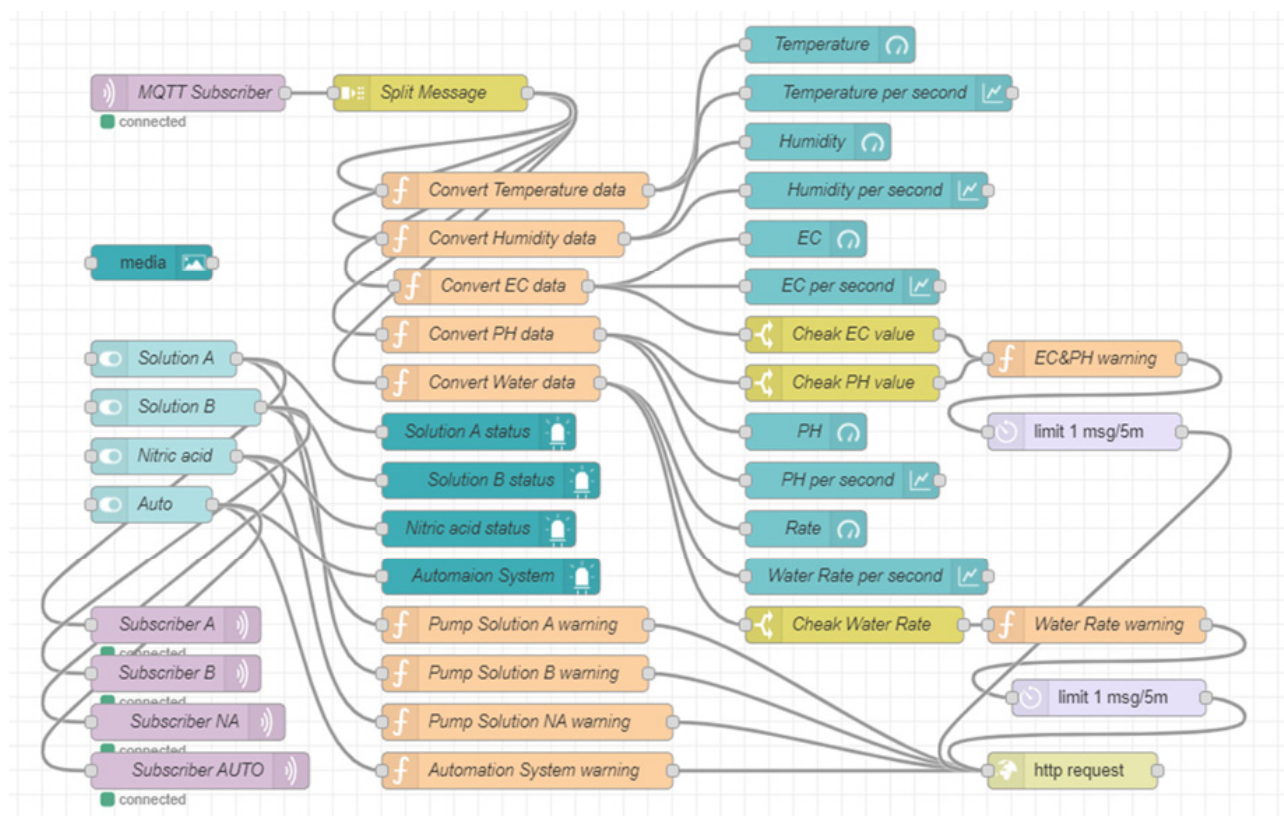


Fig. 3 Development dashboard for hydroponics controlling and monitoring system

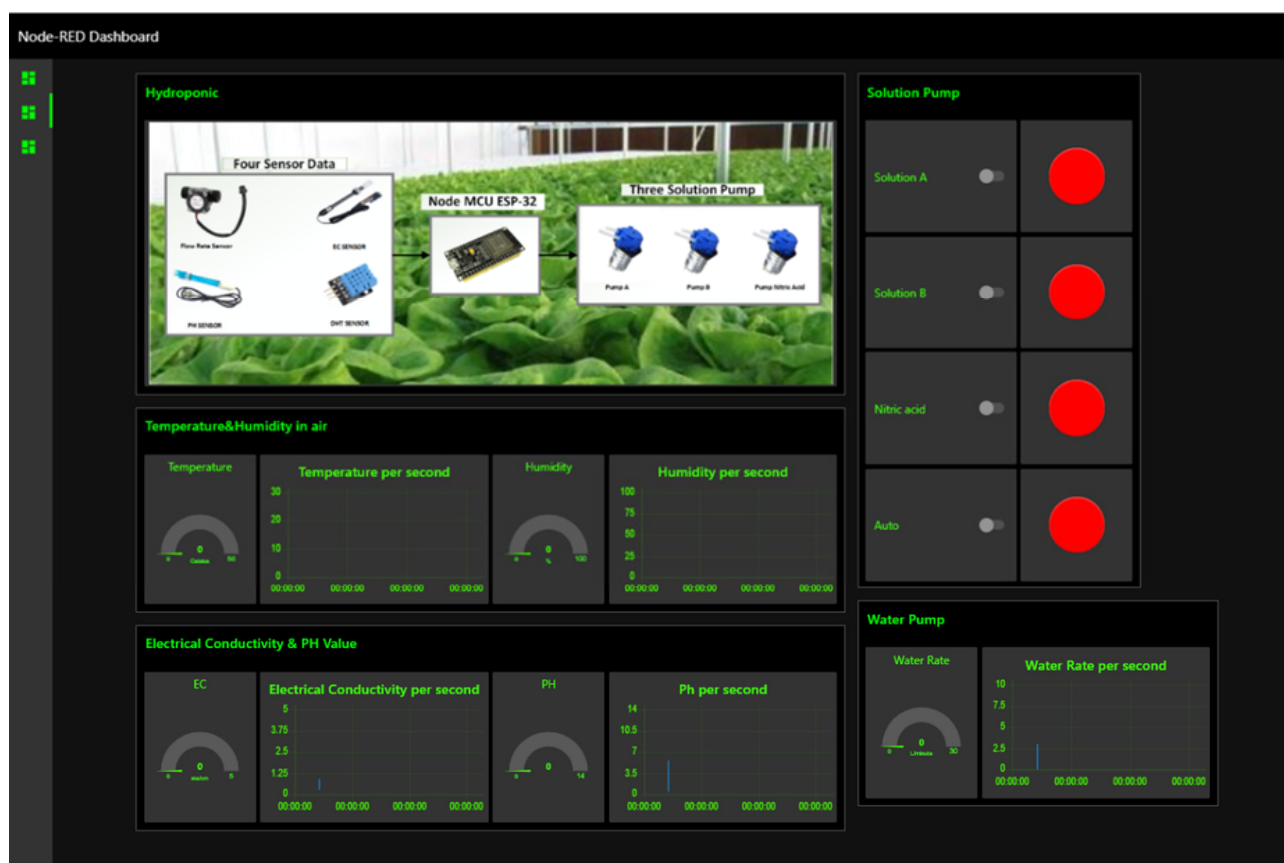


Fig. 4 Dashboard for hydroponic planting

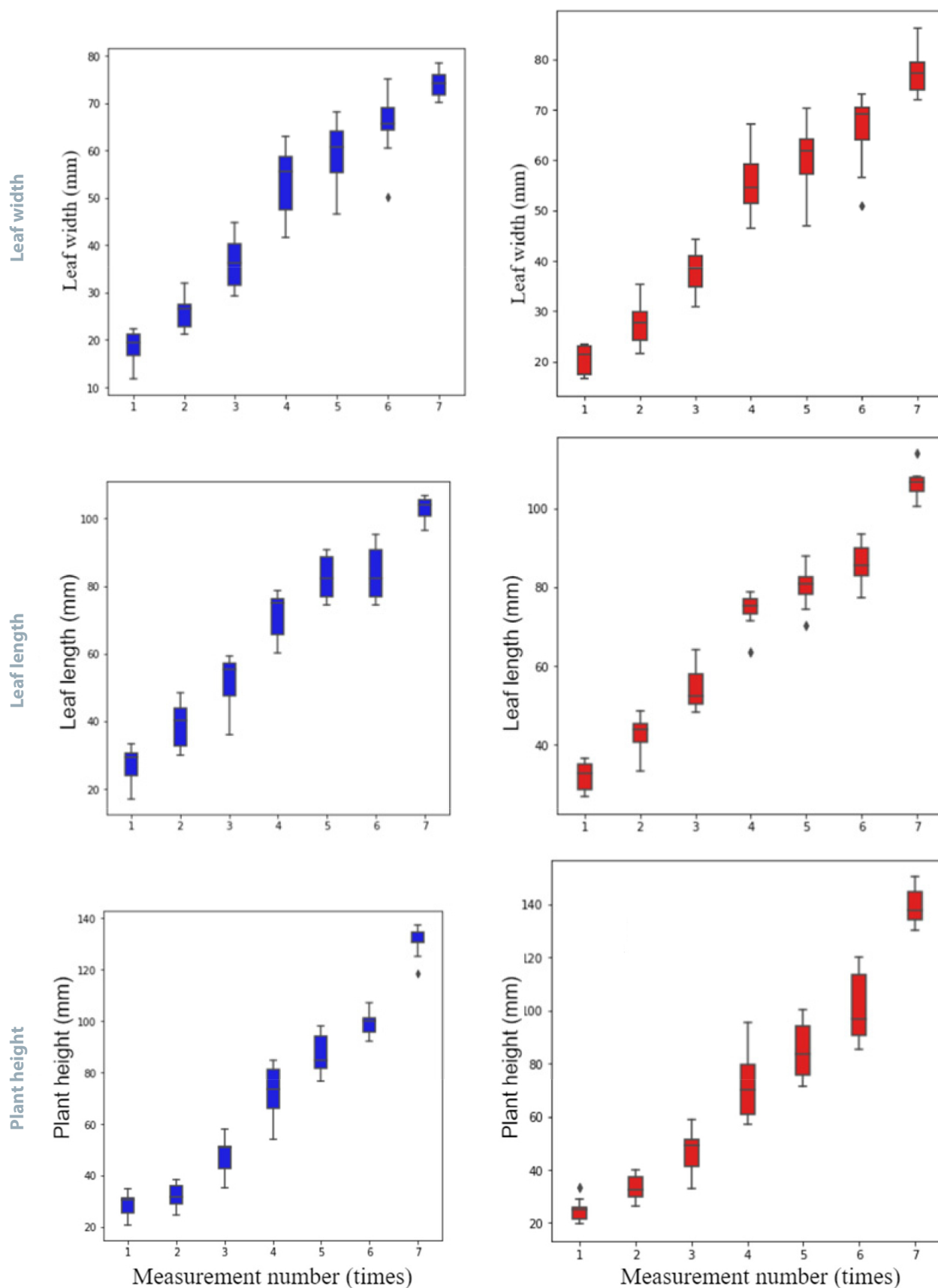


Fig. 5 The growth of Red Cos between the experimental group and the control group in terms of leaf width, leaf length, and plant height

to swiftly assess the current state of the hydroponic system in a comprehensive manner.

Another crucial aspect to consider is the incorporation of intuitive controls within the dashboard interface, as shown in Fig. 4. By integrating features such as push buttons for components like solution pumps and the ability to enable or disable automated operations, users are empowered with direct control over pivotal components. This feature greatly contributes to enhancing the ease of managing hydroponic operations, ultimately ensuring a seamless operation process.

Moreover, the implementation of a notification system stands as a critical element in alerting users promptly to any operational anomalies that may arise. By establishing alerts for deviations in EC, pH values, or water flow rates that fall below defined thresholds, users can receive notifications through LINE Notify. This approach guarantees timely responses to potential issues, thus aiding in the maintenance of optimal hydroponic conditions at all times.

The growth of Red Cos lettuce

The experiment involved measuring the growth of Red Cos vegetables in terms of leaf width, leaf length, and plant height, measured every 3 days after planting. Ten plants were randomly selected, and growth data were collected seven times, as shown in Figs 5 and 6, respectively.

The results showed that the Red Cos lettuce grown under a semi-automatic control system had higher average values for plant height, leaf length, and leaf width than those grown under normal control systems. After the seventh growth harvest, the weight data were collected and analysed. The Red Cos lettuce grown with the semi-automatic control system exhibited a mean weight of 51 grams, whereas the lettuce grown under normal control weighed 42.10 grams on average. This indicated a significant weight increase of 17.45% in the semi-automatic control group compared to the normal control group.

The findings underscore the potential advantages of semi-automatic control systems in hydroponic vegetable production. The improved growth parameter indicates that the semi-automatic system optimises nutrient delivery and environmental conditions, fostering healthier and more vigorous plant development. Furthermore, the substantial increase in lettuce weight in the semi-automatic control group emphasises the economic benefits of such systems. This weight gain not only contributes to higher yields but also enhances the overall efficiency and productivity of hydroponic farming.

Evaluating economic efficiency

The economic efficiency of the semi-automatic control system in hydroponic farming was evaluated through

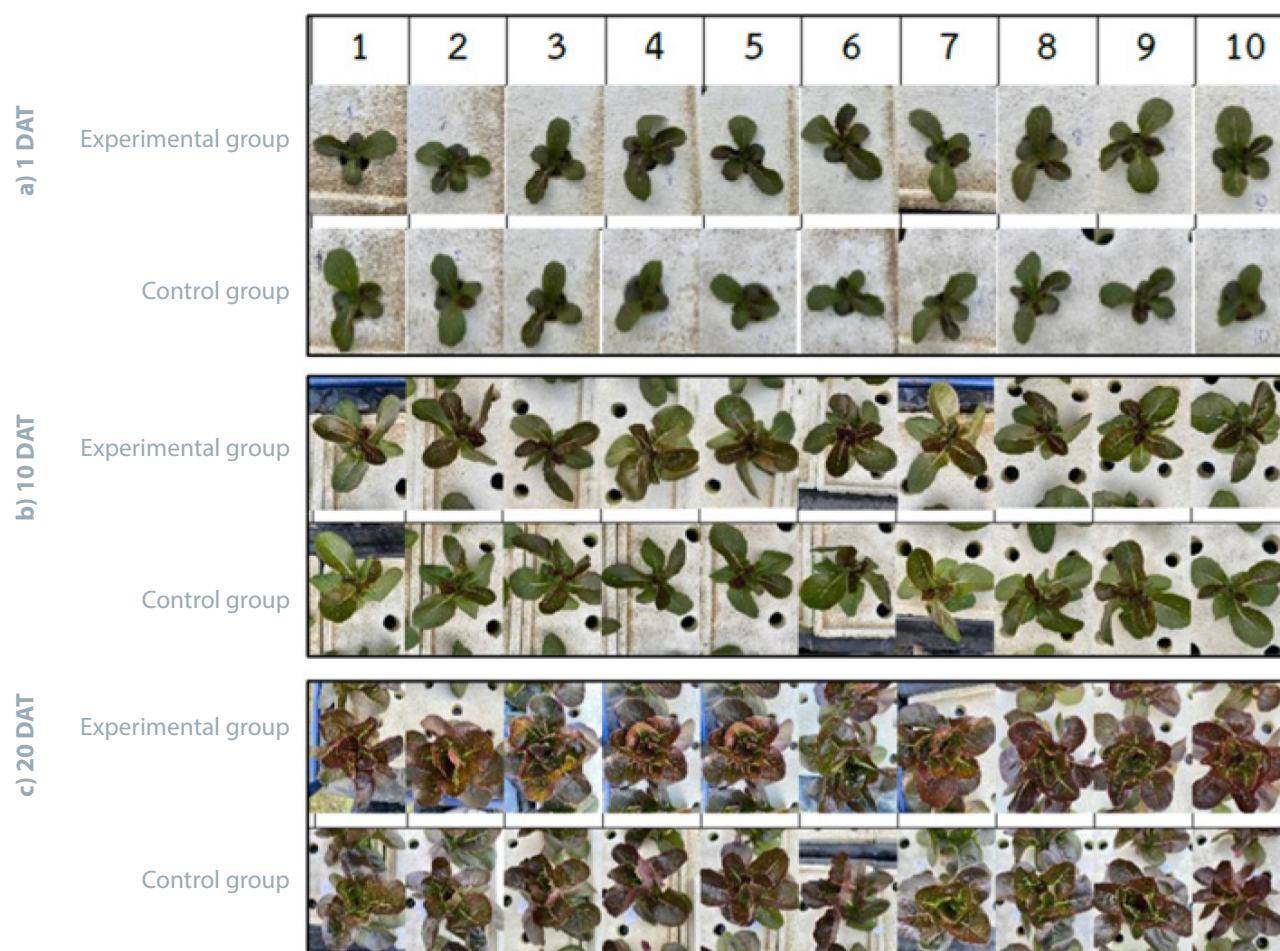


Fig. 6 Red Cos shape and size at (a) 1 DAT; (b) 10 DAT; and (c) 20 DAT

a detailed analysis of crop yield and resource utilisation. The study focused on the growth of Red Cos lettuce, comparing the performance of the semi-automatic system with the conventional control system. This increase in yield translates to higher economic returns for farmers. The semi-automatic system optimises nutrient delivery and environmental conditions, reducing the need for manual interventions and lowering labour costs. Furthermore, the improved plant health and growth rates result in a more efficient use of resources. The study also highlighted the cost-effectiveness of the semi-automatic control system. By integrating the IoT technology and real-time monitoring, the system ensures precise control over growing conditions and enhancing productivity. The control system demonstrates significant economic benefits because it enhances crop yields and reduces labour costs. This makes it a viable and attractive option for small-scale farmers looking to increase profitability and sustainability in their operations.

In discussion, it is evident that our findings closely align with those presented in several key aspects. The study specifically emphasises the integration of IoT technology into hydroponic systems. To increase efficiency and productivity in small-scale farming, our research also reinforces the documented benefits of IoT-based hydroponic systems, including real-time monitoring and precise control system. Comparisons with the work of Babakhouya et al. (2023), who explored the impact of IoT in agriculture on a larger scale, can offer valuable insights. This research highlighted the scalability of IoT solutions in optimising resource utilisation and crop monitoring, aligning with the findings of this study on enhancing productivity in small-scale hydroponic systems. By citing and comparing these results, a broader context is established, demonstrating the potential of IoT technologies across varying agricultural scales.

Moreover, the study by Cihan (2023) and Rehman et al. (2022) on the economic benefits of IoT adoption in farming practices can complement the discussion on the financial implications of integrating IoT in hydroponic setups. With reference to their findings regarding cost-effectiveness, a more comprehensive analysis of the economic feasibility of implementing IoT in small-scale agriculture can therefore be presented. This comparative method enables a detailed examination of the benefits and obstacles linked to the implementation of IoT technology in hydroponic system.

Conclusion

The study demonstrates the potential of integrating the IoT technology into hydroponic systems to enhance the efficiency and productivity of small-scale farming. By employing wireless and portable sensor nodes to monitor critical parameters such as EC, pH levels, temperature, and humidity, the system ensures optimal growing conditions for plants. The semi-automatic control system, in particular, showed superior performance in maintaining these parameters within the desired ranges, leading to healthier and more vigorous plant growth, as evidenced by the significant increase in the weight and growth metrics of Red Cos lettuce compared to the normal control system.

The economic benefits of the semi-automatic system are noteworthy, as it not only enhances crop yields but also improves the overall productivity of hydroponic farming, making it a viable solution for small-scale farmers who face challenges such as high costs and labour-intensive nutrient management. The study's findings underscore the importance of real-time monitoring and precise control in hydroponic systems, which can be achieved through the integration of IoT technologies.

Future research should focus on refining the measurement devices for better accuracy and efficiency, reducing the cost of the system without compromising performance, and integrating machine learning algorithms to predict and optimise plant growth patterns. Additionally, expanding the range of crops that can be grown using this system and studying the long-term effects of hydroponic agriculture on plant health could provide valuable insights for commercial-scale applications. This research highlights the transformative potential of smart hydroponic systems in addressing the challenges of traditional farming and contributing to global food security.

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