Scientific Reports
https://doi.org/10.1038/s41598-026-37971-4
Article in Press

Sustainable urban farming using a smart hydroponic approach using IoT and real time monitoring

Received: 2 April 2025

Accepted: 28 January 2026

Published online: 11 February 2026

Cite this article as: En L.W., Lim C.L., Kok C.L. *et al.* Sustainable urban farming using a smart hydroponic approach using IoT and real time monitoring. *Sci Rep* (2026). https://doi.org/10.1038/s41598-026-37971-4

Ley Wei En, Chong Lye Lim, Chiang Liang Kok, Yit Yan Koh & Charles C. C. Lee

Sustainable Urban Farming Using A Smart Hydroponic Approach Using IoT and Real Time Monitoring

Ley Wei En[1], Chong Lye Lim[2], Chiang Liang Kok[1,*], Yit Yan Koh[1] and Charles CC Lee[1]

[1]The University of Newcastle, Callaghan, 2308, Australia
[2]University Partnership (Coventry University), PSB Academy, Singapore
[1,*]chiangliang.kok@newcastle.edu.au

Abstract:

Sustainable farming methods are needed due to the rising demand for fresh products brought on by the world's population growth. The light and water temperature factors affect the growth of selected leafy greens, and the Internet of Things-enabled smart system helps monitor these conditions. The present project aims to explore how the water temperature and light intensity affect the growth of leafy greens by integrating an Arduino UNO WIFI microcontroller with a household hydroponic system as an Internet of Things-enabled smart home hydroponic system. The smart home hydroponic system consists of sensors, an Arduino UNO WIFI microcontroller, and a home hydroponic system. The smart home hydroponic system monitors and manages environmental variables in real-time in hydroponics. The smart home hydroponic system helps to catalyse growing conditions by monitoring the information on temperature, relative humidity (RH), pH, and nutrient concentrations. Four experimental setups combining different lighting sources (LED vs. natural light) and ambient conditions (room vs. air-conditioned) were tested over a 4-week growth period using *kale* as the model crop. The light intensity and water temperature were monitored and recorded through a cloud system. Results showed that LED lighting with room temperature conditions yielded the highest growth performance, with a 15–20% increase in leaf count and biomass compared to other conditions. The optimal water temperature range was identified as 28–30°C, and stable pH values between 6.5–7.0 were correlated with faster root development. The study demonstrates the effectiveness of using IoT sensors provides a better-controlled environment and helps improve the efficiency of hydroponic systems in an urban household setting.

Introduction:

Recent developments in smart agriculture have placed greater emphasis on integrating IoT technologies to continuously monitor and improve agricultural production settings. For example, Sharma[18] created a smart greenhouse design that automates climate control by utilizing sensor data and cloud. Similarly, Dey and Halder[19] suggested a thorough IoT-enabled hydroponic system architecture to dynamically control environmental factors and nutrient supply. These studies demonstrate the increasing significance of automation and real-time data feedback in sustainable agriculture. The idea that integrating IoT and hydroponics increases efficiency and saves resources is supported by additional data from Parab[20], particularly in urban agricultural environments.

The increase in the global population has led to a high demand for fresh produce, and the need for sustainable agricultural practices has driven significant interest in using hydroponic systems. By 2050, the world's population is expected to reach 9.7 billion, which will result in a 60% increase in food production efficiency and security to meet the growing population's demands[1]. Hence, a large amount of land is needed to grow crops (*kale*), and the land needs to be fertile to grow leafy green plants. Nevertheless, Natural disasters frequently occur worldwide, destroying crops (*kale*) and decreasing food production for the population. For example, China, a large food producer, revealed that around two hundred disasters in 2016 were recorded, leading to an indirect loss of 70% of total supply chain losses. The agriculture sector lost a total of 18%, which was caused by floods, as shown in Figure 1[2]. Natural disasters have deeply affected food production in China, as shown in Figure 1, which illustrates the total loss in billions from the destruction of natural disasters in China in different provinces and the ratio of agriculture loss due to the distinct types of disasters.

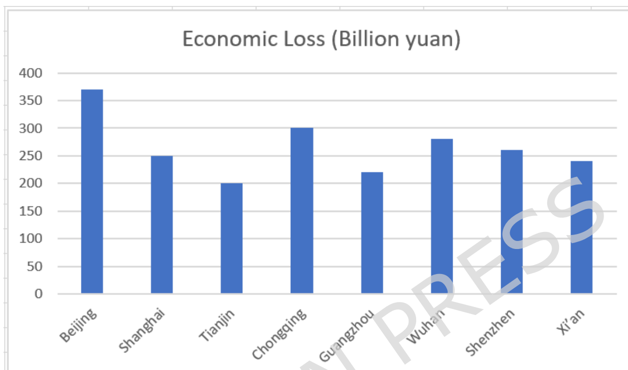


Figure 1 China's total supply chain losses due to disasters[2]

There are many distinct types of irrigation in agriculture, including sprinkler irrigation, drip irrigation, surface irrigation, micro-sprinkler irrigation, subsurface irrigation, lateral move irrigation, and centre pivot irrigation[3]. While traditional soil cultivation has always been the preferred method, increasing urbanization leads to alternative approaches such as hydroponic, which replaces soil with water, the key to crop (*kale*) cultivation[4]. A hydroponic system is one of the methods of growing plants without soil using mineral nutrient solutions, offering a promising solution to the food demand. Traditional farming methods cannot supply the global population's demand, so they use fertilizers to increase crop (*kale*) productivity. This will result in deforestation, soil degradation, water pollution, and greenhouse gas emissions. Thus, the land will become barren and lose its fertility to grow another batch of new corps[5]. The hydroponic system allows for the cultivation of crops (*kale*) in controlled environments, making it possible to grow fresh produce yearly regardless of weather conditions. Integrating Internet of Things (IoT) technology into these systems further enhances efficiency and control, offering real-time monitoring and control over all growth parameters. Figure 2 shows the transition from traditional to model farming methods where the model farming deploys smart technologies such as IoT. Globally, IoT-enabled households have increased over the years, suggesting it is the new direction and device to improve food productivity.

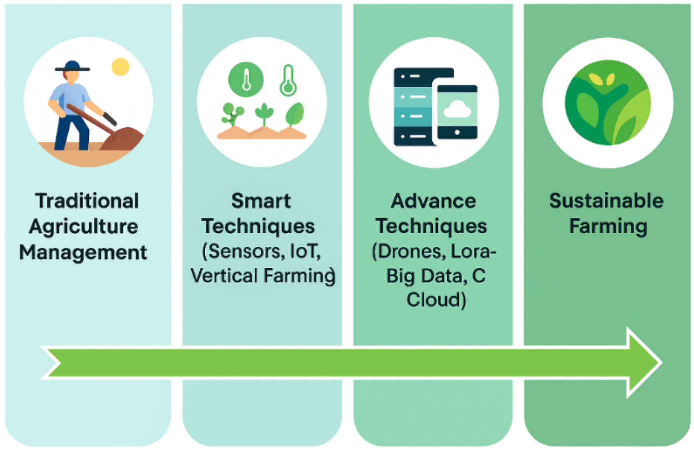


Figure 2 Transition from traditional to model farming methods[1]

Due to the limited land and high population density in Singapore, the need for sustainable food production is in high demand. The hydroponic system offers a soil-free method by utilizing controlled environments and monitoring the light and water temperature of the plant growth, which has become a popular method for growing plants in Singapore urban farming[6]. The innovation of IoT and hydroponics has driven recent advancements in urban agriculture in Singapore. IoT-enabled hydroponic systems use sensors, automation, and data analytics to enhance resource management, crop (*kale*) growth, and overall efficiency[6]. IoT enabled hydroponics to use sensors to monitor factors affecting the plant, such as temperature, relative humidity, pH levels, fertilizer concentration, and water quality. After collecting the data from the sensors, it will be transferred to a centralized system for analysis. Farmers can access this data remotely via mobile or web applications, making informed decisions and adjusting the growing conditions to suit the farm[7]. The integration of hydroponics and IoT allows for precise and dynamic management of environmental factors, ensuring the best conditions for plant growth. IoT technology can adjust variables like water flow, amount of fertilizer, and lighting based on real-time data, optimizing resource use and maximizing the gains. Additionally, IoT technology enables early detection of problems or deviations from ideal conditions, allowing us to intervene early to prevent crop (*kale*) loss[6]. This concludes that local farmers have started adapting to different urban farming techniques. As seen in Figure 3, Singapore urban farming consists of indoor urban farming using the hydroponic system in a controlled environment, vertical farming with natural lighting in a semi-enclosed greenhouse and rooftop farming with natural sunlight with controlled water. All these diverse types of urban farming share a common interest in solving land and food shortages. Farms like indoor and rooftop farms can use technologies to increase their productivity. However, it will be more costly in terms of energy consumption. While vertical farming will be less costly as it uses natural sunlight and water, productivity will be less as compared to others. This determines what solutions are available to help reduce energy usage costs.

Figure 3 Different types of urban farms in Singapore[9]

Although hydroponic systems are becoming increasingly popular in urban cities, many of the solutions are still constrained by their need for manual monitoring, lack of automation, or expensive equipment, particularly when it comes to households. The main material used now in publication concentrates on individual variable studies such as nutrients or commercial-scale operations without incorporating thorough sensor-based automation for small-scale urban use. These disadvantages show the need for a system that can dynamically control plant growth conditions in real-time that is inexpensive, modular, and accessible[18].

Throughout the experiment, it will highlight a unique smart hydroponic prototype that is IoT-enabled and designed for home settings[19]. In contrast to earlier systems, the design incorporates cloud-based data visualization, customizable lighting control schedules to mimic sunshine cycles, and real-time pH and water temperature monitoring. Four experimental sets that examine the effects of temperature and light source on *kale* development were used to validate the system.

In summary, this study aims to address the gap in low-cost, real-time, IoT-enabled hydroponic systems for household use, particularly those capable of monitoring and optimizing plant growth conditions[19]. The main contributions of this study include the development of a low-cost, IoT-enabled hydroponic prototype suitable for household use, featuring real-time pH and water temperature monitoring integrated with a cloud-based dashboard. Through a structured experiment involving four environmental setups, the system was used to analyze the effects of different lighting sources (LED vs. natural) and ambient temperatures (room vs. air-conditioned) on the growth of *kale*. The results identified optimal growing conditions, the best water temperature range from 28–30°C. By constantly expose to 16 hours of LED light, it led to a 15–20% increase in plant growth compared to other setups. Lastly, the study proposes a scalable automation framework incorporating sensor-driven nutrient dosing, lighting control, and environmental feedback, laying the groundwork for a more robust and fully autonomous hydroponic system in future works.

Research Statement

For smart cities like Singapore, an IoT-enabled household hydroponic system is an efficient way to achieve sustainable urban agriculture. Singapore's "30 by 30" initiative, led by the Singapore Food Agency (SFA), aims to strengthen national food security by producing 30% of the country's nutritional needs locally by 2030 through sustainable and innovative farming solutions [8]. This system's purpose is to include precision engineering to improve and optimize agricultural processes to maximize production. This will help Singapore increase its agricultural yields and make it self-sufficient and resilient in food production.

Project Aim and Objectives

Aim: To investigate how varying light intensities and water temperature affect the growth rate, leafy green mass, and overall plant health. The data to list the optimal conditions for maximizing the productivity of the leafy green to be collected via the IoT sensors.

Objectives:

1) Identify the required design specifications and features of an IoT-enabled household hydroponic systems
2) Design the specifications and features of IoT-enabled household hydroponic system
3) Design the circuit for IoT to collect the light and water temperature
4) Make a prototype based on selected design specifications
5) Evaluate the performance of the prototype

Materials and Methods:

The processes taken to address the Project's Aim and Objectives are represented in Figure 4 below. This facilitates the methodology used to gain results, which will be analysed for the recommendation and conclusion of the feasibility study. The process starts with identifying the key components and features of the prototype with the literature review in mind. Subsequently, it is followed by the design stage, which is choosing the hydroponic design and circuit for the control of IoT. Then, it is followed by enquiring all the components and hardware. After the materials and components are required, the prototype can be constructed. Afterwards, it is followed by testing and troubleshooting before testing it for experimentation in the study. Lastly, the data is collected and compared against each other to evaluate the best performance of the prototype.

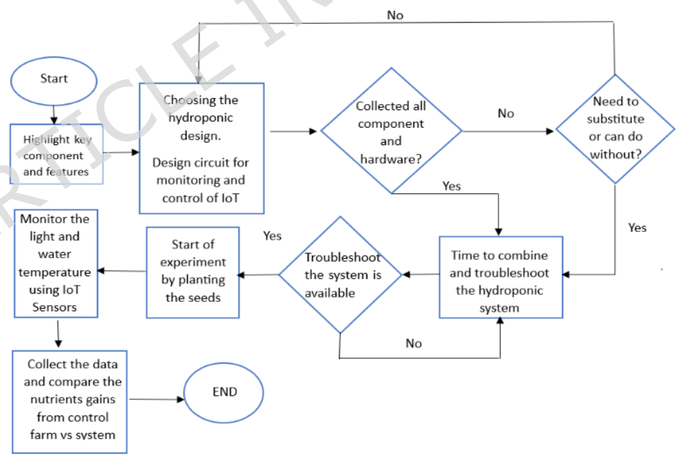


Figure 4 Flowchart of processes for the feasibility study.

Selected Model design

Figure 5 Model 1 Hydroponic Kit [10]

Model 1 from figure 5 comprises the main structure to support the growth of leafy greens. The body consists of the stand, LED grow lamp, grow basket, grow deck, water tank and Sensor pump. The stand is to connect the LED grow lamp with the water tank to ensure the plants get artificial light to grow. The water tank has a capacity of 2.5 litres maximum and 9 pods to grow the leafy greens. When the water level is below the sensors, the sensor pump will stop working and start to blink a green light to inform the user to add water to the tank. The LED light uses 12 watts of power to light up the hydroponic kit with dimensions of 380×130×115mm. The general prototype design of the IoT-enabled hydroponic system, which formed the conceptual basis of this investigation, is shown in Figure 5.

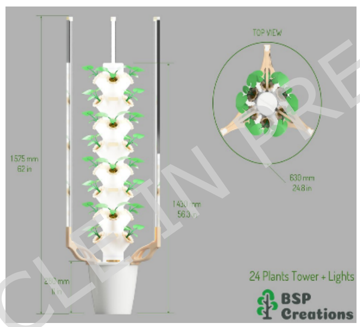


Figure 6 Model 2 Hydroponic Tower [11]

The Hydroponic Tower shown in Figure 6 is the second model, 24 Plants Tower and lights. *BSP Creations* has produced an innovative idea to save limited space in the household environment. The model has 24 pods to grow the leafy greens and 3 LED lights surrounding the plants. No water tank is below. Hence, the user needs to water the plants daily. The model has a length of up to 575mm, which may require a high ceiling in the room in the household to keep this hydroponic system.

Figure 7 Garden vegetable growing box [12]

Figure 7 which is Model 3 comprises the main structure to support the growth of leafy greens. The body consists of the grow deck, water tank and Sensor pump. However, Figure 3.3 has no LED light to support the plant's growth, which implies a need for extra design specifications to be added to the model. The water tank has a capacity of 3 litres maximum and 6 pods to grow the leafy greens.

Next, three models were evaluated using a multi-criteria decision-making (MCDM) approach, where scores were assigned to key parameters (appearance, ergonomics, energy efficiency, material selection, and cost). The total scores provide a comparative assessment of the prototype overall suitability for the best hydroponic setup in a household environment.

Table 1 Multi-criteria evaluation of three models (MCDM)

	Model 1	Model 2	Model 3
Appearances	4	3	4
Ergonomics	5	3	3
Energy	4	3	3
Material	3	4	3
Cost	4	3	5
Total	20	16	18

Based on Table 1, after careful consideration and thinking, model 1 is the most suitable choice for the IoT experiment in a household environment. Although the cost is high and its materials are not the most eco-friendly, the advantages outweigh the disadvantages. The model's appearance is presentable within the household's limited spacing, making it ideal for household farming. Furthermore, the energy consumption is lower compared to other models, which will help save electricity bills in the long run. Although the overall cost of prototype model 1 is slightly higher compared to the other models, its user-friendly setup and installation help make it accessible even for individuals with no knowledge of the prototype. This prototype and its appealing design encourage users to be more interactive when growing plants. It will help foster a strong connection between the users and their plants and, in return, help Singapore promote sustainable living and appreciation for indoor household farming.

Figure 8 Final prototype for model 1

Figure 8 shows the completed and functional system, illustrating the final implemented design. The development process is shown by this journey from prototype to final design, which shows how the basic model was improved into a working hydroponic system with real-time monitoring and data transfer capabilities. When combined, the data offer a comprehensive picture of the system's development from conception to actual use.

As shown in Figure 9, the IoT system integrates the Arduino UNO WiFi with the DS18B20 temperature sensor, pH sensor, and OLED display. The sensors provide real-time environmental readings, which are displayed locally on the OLED and transmitted to the Blynk IoT platform. The water pump is connected through a relay to enable circulation of the nutrient solution. The monitoring system is made up of sensors to collect data and notify the user if any unwanted changes are off. The temperature sensor tracks the water temperature, and the Analog PH sensor meter is used to monitor the nutrient level of the water daily. It will be supplied by a 9V battery which is connected to the Arduino UNO WIFI. Furthermore, the 9V battery served as a backup power supply for the Arduino UNO WiFi microcontroller and sensors to ensure continuity in data logging during short power interruptions. This will allow the user to closely monitor the experiment using an IoT system from anywhere via the internet.

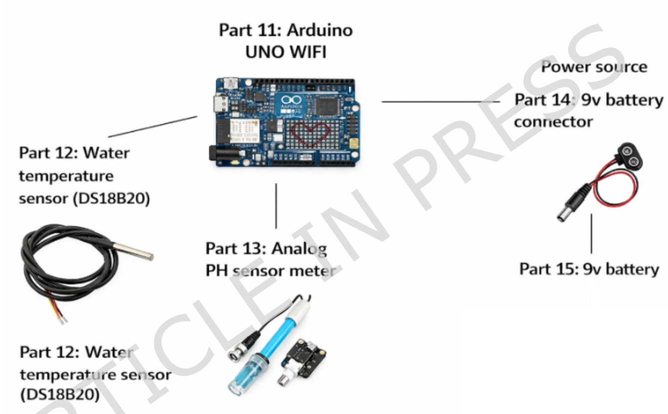


Figure 9 Diagram of components that make up the Circuitry system.

The next step is to collect all the components needed to combine the power and control systems. The main energy source comes from the power cord and controller, which are connected to an electrical plug. The model comes with a controller that controls and regulates the input and output of electrical energy. Additionally, there is a pump in the water tank to ensures continuous circulation of the nutrient solution, which helps maintain uniform water temperature in the tank. While the pump does not directly control plant temperature, the stabilized root-zone temperature indirectly contributes to consistent plant growth. A grow lamp with an LED light creates artificial sunlight for the leafy greens to grow in the grow sponges. Figure 9 shows how the components will be connected to create an IoT monitoring and control system.
Table 2 helps to consolidate all the components by giving further details and helps to keep track of the components and quantities needed for the experiment.

In our study, the LED grow lamps were fixed at a constant height of 28 cm above the canopy at the start of the experiment, ensuring uniform irradiance across the growth area. As the plants grew taller, the lamp height was manually adjusted once per week to maintain a consistent light distance and prevent excessive elongation. Regarding light measurement methodology, the photosynthetic photon flux density (PPFD) of approximately 300

$\mu mol \cdot m^{-2} \cdot s^{-1}$ was measured using a portable quantum PAR meter prior to each experiment. To ensure spatial uniformity, 10 sampling points were taken across the growth deck. The average of these measurements was reported as the target PPFD value in the manuscript. For the slight etiolation and bending in some seedlings, we also noticed during the early germination stage before full leaf emergence, and in the natural-light setups, where fluctuating sunlight caused directional growth.

Table 2 All the components

Part Number:	Name of the parts	Description / Function	Key Specifications (Range/Details)	Quantity	Part Number:
1	The stand	Structural support with connectors	Custom acrylic frame, modular connectors	1	1
2	Grow lamp	Provides light for photosynthesis	Full-spectrum LED, 20W, 400–700 nm range	1	2
3	Cap	Covers seedlings to retain humidity	Transparent plastic, 5 cm height	1	3
4	Grow basket	Holds grow sponges and plants	Diameter: 2.5 cm, reusable plastic	9	4
5	Grow Deck	Base structure supporting baskets	ABS plastic, fits 9 baskets	1	5
6	Water tank	Stores nutrient solution	Capacity: 20L	1	6
7	Pump in the water tank	Circulates nutrient solution in the tank	3–6V DC, Flow rate: ~120 L/hr	1	7
8	Power Cord & Controller	Supplies and regulates power to devices	AC 100–240V input, DC 5V/9V output	1	8
9	Grow Sponges	Substrate to hold seeds	Biodegradable sponge material, 2.5 cm diameter	9	9
10	Plant food A & B	Nutrient solutions for hydroponics	NPK + Ca, Mg mix; EC 1.5–2.0 mS/cm	2	10
11	Arduino UNO WIFI	IoT microcontroller for system control	Built-in WiFi, 14 digital I/O pins, 5V logic	1	11
12	Water temperature sensor (DS18B20)	Measures water temperature	Range: -55°C to +125°C, Accuracy: ±0.5°C	1	12
13	Analog PH sensor meter	Measures pH of nutrient solution	Range: 0–14 pH, Accuracy: ±0.1 pH	1	13

14	9V battery connector	Connector for backup power	Standard snap-on connector for 9V battery	1	14
15	9V battery	Backup power supply	9V alkaline battery	1	15

Components selection

As shown in Figure 10, a hinge can be combined with the stand and moved up and down depending on the user. Although LEDs have a higher cost than others, their advantages in energy efficiency, heat usage, and environmental sustainability make them the most optimal choice for household hydroponic systems.

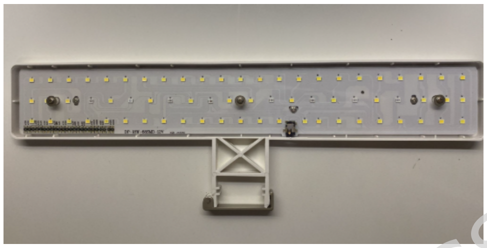


Figure 10 The chosen LED lights

At the same time, Figure 11 below illustrates the stand which connects the LED light to the water tank. The distance is measured to be 28 cm. This spacing is calibrated to ensure that the light emitting from the LED covers all the leafy greens, promoting uniform growth and photosynthesis for the experiment.

Figure 11 The chosen stand

In the beginning stages of growth for the leafy greens, placing caps on the plants helps to create a controlled and healthy environment that supports optimal development. One key benefit of the caps is that they shield the plant roots and nutrient solution from excessive light exposure from LED lights, which will prevent algae from growing. Algae will compete with plants for nutrients and oxygen, which will affect the experiment's progress. Also, it will aid in retaining moisture around the roots to ensure consistent hydration for the young plants. Additionally, caps provide protection by keeping dust and other contaminants out of the nutrient solution, which reduces the risk of harmful bacteria. They help to regulate the temperature around the seedlings and provide nutrient solutions, which is important during the early stage of development. Furthermore, they help keep the plants upright as they grow and protect the roots from damage. Overall, the figure 12 which are the caps help the plants thrive during the early growth phases by eliminating harm. The below figure shows the cap placed on the sponge.

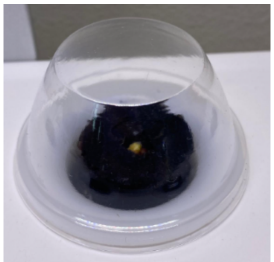


Figure 12 Cap

Below are the leafy green grow baskets, which help securely hold the growing support, such as pellets or rock wool. The experiment uses rock wool as it is soft and able to absorb moisture at a rapid pace. It also anchors the plant roots and ensures the plant grows upright and well-positioned to receive maximum light. Another important function of grow baskets is allowing the roots to grow through their openings into the nutrient-rich solution in the water. This ensures that the roots are consistently exposed to water, nutrients, and oxygen, which are all essential for growth. It also prevents the roots from becoming waterlogged and promotes a robust root system. In addition to providing support and efficient nutrient intake, grow baskets can be reused in the hydroponic systems. They are made of durable, non-toxic plastic materials that allow the users to clean and reuse them for multiple growing cycles as shown below in figure 13.

Figure 13 Grow basket

From Figure 14, the main base of the experiment is a water tank and pump in a hydroponic system. The final prototype employed a water tank with a capacity of 2.5 L, integrated with a small DC pump to circulate the nutrient solution. The hydroponic method used was a Deep Water Culture (DWC) approach, where plant roots are suspended directly in the nutrient-rich solution, supported by grow sponges and baskets. Continuous circulation ensured oxygenation and uniform nutrient distribution. Maintaining the water tank eliminates the traditional method of using soil while giving the user precise control over the growing conditions of the plants in a household environment. Inside the water tank is a pump to circulate the nutrient solution throughout the system. It ensures that the essential minerals are distributed evenly to all the plants so that there will be uniform growth and prevent the lack of nutrients. Having regular circulation prevents the solution from becoming stagnant, reduces potential algae growth, and maintains oxygen levels vital for the roots. When the water level is below the sensors, the pump stops working and blinks a green light to inform the user to add water. Together, both play a key role in maintaining the amount of nutrients the plants get throughout the hydroponic system. The pump filled with nutrient solution prepared by mixing water with standard hydroponic nutrients. This solution provided the essential minerals for plant growth and was continuously circulated and monitored. Lastly, both only need simple maintenance and are easy to use, which is a key factor for household hydroponic systems.

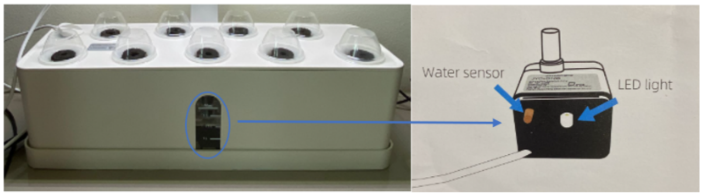


Figure 14 water tank and pump

Figure 15 illustrates that both nutrient solutions A and B are formulated to provide the best nutrition for plants. Each solution contains a distinct set of nutrients that are combined to support the growth of the leafy greens.

Nutrient Solution A contains a more variety of mixed micronutrients as compared to solution B. It contains nitrogen (N), soluble phosphorus (P_2O_5), potassium (K_2O), magnesium (Mg), and iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and boron (B). All the nutrients mentioned play a critical role in the development of the plants. For example, nitrogen supports leaf growth, phosphorus helps root development and energy flow, and potassium improves plant health. Meanwhile, the others with a shared name, EDTA-Fe, Mn, Cu, Zn ensure efficient absorption and avoid deficits, promoting vital functions such as photosynthesis, enzyme activation, and the integrity of cell structure. On the other hand, nutrient solution B focuses on calcium oxide (CaO) with additional Nitrogen (N). Calcium provides a strong cell wall to prevent leaf curling, disrupting the absorption of light. The additional nitrogen helps to ensure the plant receives a balanced and sufficient supply for the leaf growth. This dual-solution strategy prevents any imbalances in nutrients and deficiencies in growth and optimizes the systems' operating efficiency. The other benefit of separating these chemical nutrients into two nutrient solutions is that it avoids any chemical reactions causing precipitation to occur, thus keeping all nutrients in a soluble form where they are readily available for plants to take up. This is especially important in hydroponic farming because nutrient intake at the beginning stage is sensitive and crucial.

Figure 15 Nutrient solutions A & B

As for monitoring the temperature and pH values of a hydroponic system, two sensors are preferred, which are the Water Temperature Sensor (DS18B20) and the Analog pH Sensor Meter, because they are consistent, accurate, and have the appropriate specifications for the system. As seen below in figure 16, the sensors are crucial since they give reliable and precise measurements needed for systems operations. The digital DS18B20 water temperature sensor, with an exceedingly small margin of error of approximately 0.5 degrees Celsius, was chosen because it has a digital output, which consequently reduces signal noise as compared to the analogue type, which is standard. Based on the data in figure 16, the DS18B20 temperature sensor has more consistent data, resulting in higher accuracy than the Digital

Thermostat. This water sensor is intended for contact with and immersion, enabling it to adequately measure the water's temperature in the nutrient solution for hydroponic systems. It is also durable due to its waterproof design and ONE-WIRE technology, which allows many sensors to be connected to the system without multiple wires. Such key features enhance the ability of the DS18B20 in areas where it is critical to maintain the water temperature in the range of 18-24 degrees, which is needed for plants' absorption of nutrients and their development.

No	Time	Temperature(°C)		Difference	Measurement Accuracy (%)
		DS18B20 *Waterproof*	*Digital Thermostat*		
1	13.33	29.30	29.7	0.40	98.65
2	13.36	29.32	29.7	0.38	98.72
3	13.39	29.32	29.7	0.38	98.72
4	13.42	29.40	29.4	0.00	100.00
5	13.45	28.99	29.1	0.11	99.62
6	13.48	29.56	29.2	0.30	98.98
7	13.51	29.67	29.2	0.47	98.41
8	13.54	29.88	29.3	0.58	98.05
9	13.57	30.01	29.4	0.61	97.96
10	14.00	30.11	29.7	0.41	98.63
Average		**29.55**	**29.44**	**0.36**	**98.77**

Figure 16 DS18B20 Waterproof vs Digital Thermostat accuracy [13]

In the same way, the Analog pH Sensor Meter was used in the system because of its ability to take accurate and real-time pH measurements, which is crucial in maintaining nutrient concentrations in a hydroponic system. The sensor was designed to determine pH in water-based solutions. Based on figure 17, the pH Meter Analog Kit is more accurate than the Digital pH Meter. Hence, an analog pH sensor meter is optimal for better results. The analog pH sensor meter is also compatible with microcontrollers such as the Arduino UNO WIFI due to its simplicity and easy integration into system components. The sensor's accuracy has been verified through regular calibration and within the recommended range of 6 to 7 for most leafy green during the growth period [13].

No	Time	pH		Difference	Measurement Accuracy (%)
		pH Meter Analog Kit	*Digital pH Meter*		
1	13.33	7.11	7.0	0.11	98.45
2	13.36	7.09	7.0	0.09	98.73
3	13.39	7.09	7.0	0.09	98.73
4	13.42	6.92	6.9	0.02	99.71
5	13.45	6.80	6.9	0.10	98.26
6	13.48	6.68	7.0	0.40	94.28
7	13.51	6.76	6.9	0.14	96.84
8	13.54	6.79	6.8	0.01	99.85
9	13.57	7.23	6.8	0.43	94.60
10	14.00	7.16	6.7	0.46	93.57
Average		**6.95**	**6.9**	**0.18**	**97.25**

Figure 17 pH Meter vs Digital pH meter [13]

Alternative sensors were considered but not appropriate for this application. For example, other thermistors for temperature sensors for this purpose do not have the waterproof feature nor the digital output provided by the DS18B20, making it indispensable with respect to this system. Similarly, manual pH strips or litmus paper, which are other forms of determining pH level, do not provide the functionality that the pH Sensor Meter does, which is continuous and automated monitoring as shown in figure 18 below.

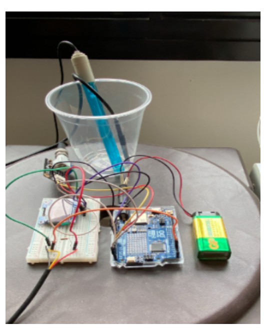


Figure 18 Selection of Water Temperature Sensor (DS18B20) and the Analog pH Sensor Meter

Testing and Troubleshooting

An open-source platform called Arduino has been deployed to help us send the data to the users. However, an understanding of the programming is needed to learn and read how each code works from online codes made readily available online for each component. This is critical when integrating several different codes to form the smart IoT system for my experiment. The system programming used is shown below in Figure 19.

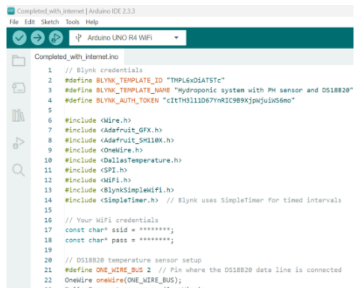


Figure 19 System Programming

The screen capture above shows the initial start of the working code for the system used in the experiment. As the main sensors are temperature sensors and pH analog sensor, there are many different iterations; thus, there are many rounds of debugging the codes when combined. Due to the capability of Arduino UNO R4 WIFI, it helps to connect to the internet and transfer data to store it in an online server. The data collected were sent to the Blynk app, as shown below in Figure 20.

Figure 20 Blynk application

Blynk is an open IoT platform that enables sensor data from the Arduino microcontroller to be collected and stored through the Internet. This system transmitted data to the platform at 60-second intervals, facilitating real-time monitoring and analysis. For a more comprehensive analysis, the collected data were exported to Excel for further processing. Once the functionality of each individual component was thoroughly tested and understood, they were seamlessly integrated into a smart system. This integration was achieved using the Arduino UNO WIFI microcontroller and programmed through the Arduino IDE.

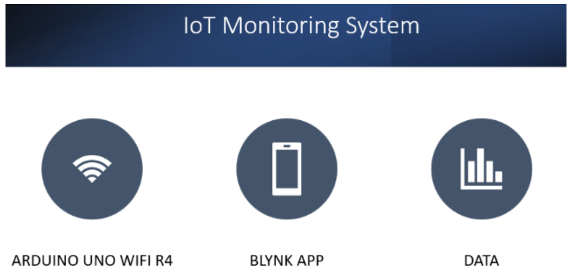


Figure 21 IoT Monitoring System

From figure 21 above, the IoT monitoring system starts by letting the Arduino UNO WIFI module first connect to your home WIFI network using the provided SSID and password. This establishes a stable internet connection, allowing the Arduino to communicate with external servers. Once connected to WIFI, the code initializes a connection with the IoT platform server (like Blynk) using an authentication token. This token verifies the device with the server. Then, the server acts as a bridge, receiving data from the Arduino and sending it to the user's app or dashboard in real-time. Afterwards, the Arduino collects data from sensors (e.g., pH, temperature) and sends this data to the server at regular intervals. The server processes and logs this data, displaying it on the dashboard or app for real-time monitoring. The power cord and controller control the LED and water pump voltage, both are set with 16 hours of work and 8 hours of rest in a day. The LED light is set to mimic the cycle of the sun when it rises and sets, the first 2 hours cover only 50% brightness to act as sunrise, then 12 hours to 100% brightness to act as noon, where the sun is at the highest and hottest, last 2 hours of 50% brightness to act as the sunset. The pump works in an interval of 10 minutes and 10 minutes of rest in a cycle for 16 hours straight. The combined voltage of the LED and water pump throughout the day is 12 watts.

Pseudocode of IoT Hydroponic Monitoring and Control System

```
// Blynk credentials
#define BLYNK_TEMPLATE_ID "TMPL6xDiAT5Tc"
#define BLYNK_TEMPLATE_NAME "Hydroponic system with PH sensor and DS18B20"
#define BLYNK_AUTH_TOKEN "cItTH3l11D67YnRIC9B9XjpWjuiWS6mo"

#include <Wire.h>
#include <Adafruit_GFX.h>
#include <Adafruit_SH110X.h>
#include <OneWire.h>
#include <DallasTemperature.h>
#include <SPI.h>
#include <WiFi.h>
#include <BlynkSimpleWifi.h>
#include <SimpleTimer.h>  // Blynk uses SimpleTimer for timed intervals

// Your WiFi credentials
const char* ssid = "*******";
const char* pass = "*******";

// DS18B20 temperature sensor setup
#define ONE_WIRE_BUS 2
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);
```

```
// pH sensor setup
float calibration_value = 15.00 - 0.31;
int pHsensor = A0;
int buffer_arr[10], temp;
float ph_act;
unsigned long int avgval;

// SH1106 OLED display setup
#define SCREEN_WIDTH 128
#define SCREEN_HEIGHT 64
Adafruit_SH1106G display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire, -1);

float temperatureC;
SimpleTimer timer;

void sendData() {
  Blynk.virtualWrite(V0, ph_act);
  Blynk.virtualWrite(V1, temperatureC);
}

void setup() {
  Serial.begin(9600);
  #define BLYNK_PRINT Serial
  Blynk.begin(BLYNK_AUTH_TOKEN, ssid, pass);

  if (WiFi.status() != WL_CONNECTED) {
    Serial.println("WiFi not connected");
  } else {
    Serial.println("WiFi connected");
  }

  sensors.begin();

  if (!display.begin(0x3C, true)) {
    Serial.println(F("OLED allocation failed"));
    while (1);
  }

  display.clearDisplay();
  display.setTextColor(SH110X_WHITE);
  display.setTextSize(1);
  display.setCursor(0, 0);
  display.println("Initializing...");
  display.display();
  delay(2000);

  timer.setInterval(60000L, sendData);
}

void loop() {
  for (int i = 0; i < 10; i++) {
    buffer_arr[i] = analogRead(pHsensor);
    delay(30);
  }
```

```
  for (int i = 0; i < 9; i++) {
    for (int j = i + 1; j < 10; j++) {
      if (buffer_arr[i] > buffer_arr[j]) {
        temp = buffer_arr[i];
        buffer_arr[i] = buffer_arr[j];
        buffer_arr[j] = temp;
      }
    }
  }

  avgval = 0;
  for (int i = 2; i < 8; i++) {
    avgval += buffer_arr[i];
  }

  float volt = (float)avgval * 5 / 1024.0 / 6;
  ph_act = -3 * volt + calibration_value;

  sensors.requestTemperatures();
  temperatureC = sensors.getTempCByIndex(0);

  Serial.print("pH Value: ");
  Serial.println(ph_act);
  Serial.print("Temperature: ");
  Serial.print(temperatureC);
  Serial.println(" °C");

  display.clearDisplay();
  display.setTextSize(2);
  display.setCursor(0, 0);
  display.print("pH: ");
  display.print(ph_act, 2);

  display.setTextSize(2);
  display.setCursor(0, 30);
  display.print("Temp: ");
  display.print(temperatureC, 1);
  display.print(" C");

  display.display();

  if (!Blynk.connected()) {
    Serial.println("Blynk not connected");
  } else {
    Serial.println("Blynk connected");
  }

  Blynk.run();
  timer.run();
}
```

Experimentation

The experimental phase of this study involved four distinct setups aimed at investigating the impact of light source LED and natural light and temperature conditions in room and air-conditioned on the growth of leafy greens in a controlled IoT-enabled household hydroponic system. The leafy greens chosen for this experiment were *Kale* due to their rapid growth cycle and relevance to urban farming. Each experiment was conducted over a period of 4 weeks to ensure consistent growth measurements and data collection. Each setup included 9 *kale* plants grown simultaneously. The experiment was conducted once for each of the four setups to ensure reproducibility. When choosing which leafy green is best suited for the household environment, *kale* and basil seeds were chosen based on their rapid growth. However, *kale* is chosen as the better option due to faster growth, live expectancy, and lower water intake compared to basil seeds. Tuscan *Kale* is used, as shown below in Figure 22.

Figure 22 Tuscan *kale*

At the start of the experiment, *kale* seeds were placed into the grow sponge, as shown below in Figure 23. For each *kale* seed to grow upright and fast, 3 seeds were chosen to place in each grow sponge and into the grow basket. As the plants grow, they will start to compete with one another for sunlight and water. Hence, by giving more space for each seed in a growing sponge, they will compete less with one another.

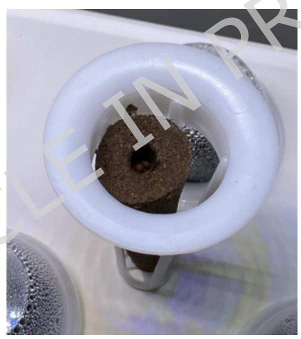
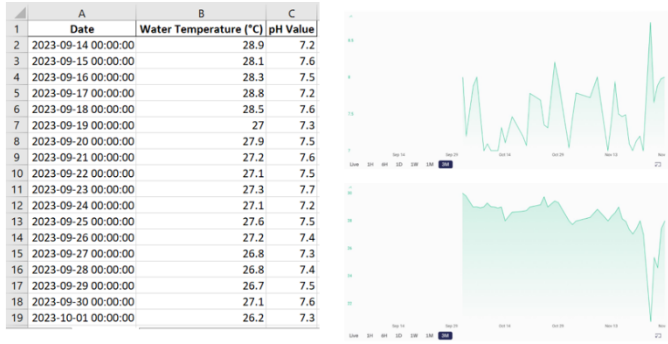


Figure 23 3 *kale* seeds inside the sponge and grow basket

Afterwards, individual grow baskets filled with seeds are placed inside the grow deck up to a maximum of 9 grow holes. The water tank is filled up to the brim with 2.5 litres of water, and nutrient solutions A and B are added afterwards to provide food for the plants. All the sponges will soak up the water and transfer the water to the seeds placed inside the growing basket. Raw data were sent and collected on Blynk for each of the experiments. The raw data were used to measure the monitored parameters taken by each experiment over a span of 3-4 months, as seen in the screen capture in Figure 24.



Date	Water Temperature (°C)	pH Value
2023-09-14 00:00:00	28.9	7.2
2023-09-15 00:00:00	28.1	7.6
2023-09-16 00:00:00	28.3	7.5
2023-09-17 00:00:00	28.8	7.2
2023-09-18 00:00:00	28.5	7.6
2023-09-19 00:00:00	27	7.3
2023-09-20 00:00:00	27.9	7.5
2023-09-21 00:00:00	27.2	7.6
2023-09-22 00:00:00	27.1	7.5
2023-09-23 00:00:00	27.3	7.7
2023-09-24 00:00:00	27.1	7.2
2023-09-25 00:00:00	27.6	7.5
2023-09-26 00:00:00	27.2	7.4
2023-09-27 00:00:00	26.8	7.3
2023-09-28 00:00:00	26.8	7.4
2023-09-29 00:00:00	26.7	7.5
2023-09-30 00:00:00	27.1	7.6
2023-10-01 00:00:00	26.2	7.3

Figure 24 Raw data on Microsoft Excel and graph on Blynk

Validation of Results

To ensure the reliability and accuracy of the numerical data collected from the hydroponic system, several validation methods were employed. First, sensor readings for water temperature (DS18B20) and pH were periodically cross validated using manual measurement tools, including a digital handheld pH meter and a traditional laboratory thermometer. Although fluctuations were minimal under LED lighting, the DS18B20 sensor was included to ensure real-time monitoring, detect transient variations, and validate system stability. It also provided critical data when natural light and air-conditioned conditions caused deviations. This helped confirm the calibration accuracy of the sensors integrated with the Arduino system. Second, using a predetermined measurement technique, plant growth parameters like leaf count, stem length, and root length were manually monitored at regular intervals. Each plant was taken with three separate measurements and added up to average the score for the data. This guaranteed uniformity in data recording and decreased human error. Daily data logging was also utilized to monitor variations and spot outliers, which were examined and eliminated if they were determined to be the result of sensor irregularities or transmission mistakes. The robustness of the results is ensured by the fact that every data point in the final analysis shows consistent and verifiable patterns across all setups.

Results and Discussions:

There were 4 different experiments carried out in an IoT-enabled household hydroponic system. The first 2 are at room temperature, but one with LED light while the other is in natural light settings. While the last two will take place in air-con temperature and, one with LED light and the last with natural light. The data collected using an IoT system combined with the growth of leafy greens for the first setup is shown below.

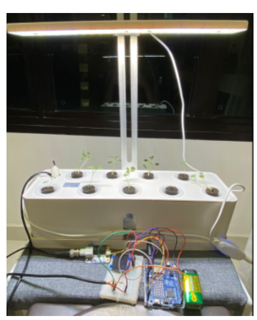


Figure 25 First experiment

As shown above in Figure 25, the setup is at room temperature with LED lights. For the first few days, the seeds were put into the sponge soil into the grow basket and partially submerged in water over a span of 3 weeks. At the start, caps were placed onto the plant to help contain the moisture and prevent algae growth in the initial stages. The grow basket will be utilized in every experiment since they facilitate the soil's absorption of water, which enables the seed to obtain water more quickly. Additionally, it provides a framework that allows the roots to grow downward rather than sideways in order to reach the water. When the *Kale* grew, the cap was removed and visually assessed how well they did in the first environment. Factors such as the number of leaves, stem thickness, and length of the roots will give the user an idea on how the plants were growing. The various stages are shown below in Figure 26.

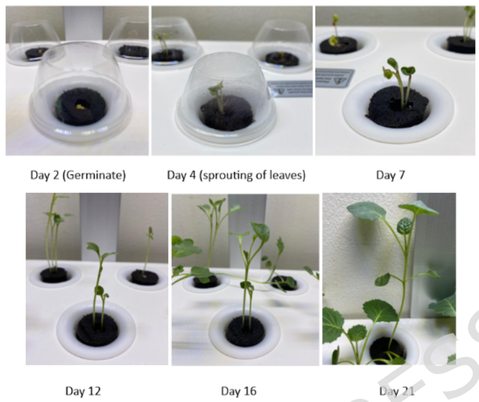


Figure 26 Stages of growth for Experiment 1

The *kale* seeds sprout from day 1 to day 2; however, some are still in seedlings. After 3-4 days, most of the seeds sprouted, and the roots started growing out to the bottom, indicating that it was time to remove the caps. After removing the caps, the places were left alone to grow upright without any issues. Afterwards, to day 14, the leafy greens grew at a steady, healthy place; the leaves were growing dark green, and the roots were growing out well. However, on day 14, every 2 weeks, the water needs to change to ensure that new micro-food is given to the *Kale* to absorb and grow faster. When changing the water tank's water, algae was observed forming in the water tank, and the colours of the water turned brown. As the readings from the water and light temperature monitoring were stable and within the healthy range of the plants, no changes were made throughout. For the rest of 7-21 days, the plants are left alone and monitored by the IoT system to see whether there are any drastic changes to inform the user. For the second experiment, the room temperature remains the same, but instead of using LED lights, it is changed to natural light. As shown in Figure 27, the setup is placed near the window to get the natural lighting to reach the plant. Caps were still used at the start to contain the moisture and prevent early algae growth within the germination process. The factors accounted are the same as in experiment 1, number of leaves, stem thickness, and length of the roots.

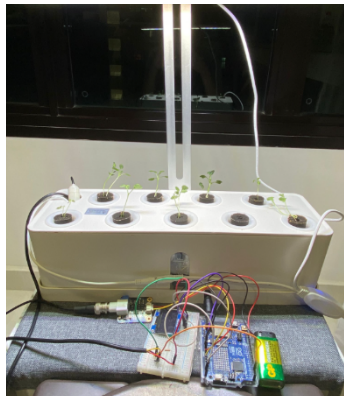


Figure 27 Stages of growth for Experiment 2

From day 1 to day 4, the *kale* seeds start to sprout; however, some are still in seedlings. After 5-7 days, most seeds sprouted, and roots started growing out to the bottom, indicating that it was time to remove the caps. Afterwards, to day 14, the leafy greens grew at a slow pace; leaves were starting to grow, the colour was light green, and the roots were growing out. On day 14, every 2 weeks, there is a need to change the water to ensure that new micro-food is given to the *Kale* to absorb and grow faster. When changing the water in the water tank, algae were also observed forming. As the readings from the water and light temperature monitoring were stable and within the healthy range of the plants, no changes were made throughout. For the rest of 7-21 days, the plants are left alone and monitored by the IoT system to see whether there are any drastic changes. However, it can be observed that the plants grow slower when LED lights are used. Natural lights are subjected to changes depending on the weather; the setup takes place from October to November, marking the start of Singapore's monsoon season. This meant that the plants were undergoing adverse temperature changes during each day. It will have subjected the plants to sudden changes in temperature and light intensity from natural light.

28	2023-10-10 00:00:00	25.4	7.7	Cloudy
29	2023-10-11 00:00:00	25.2	7.5	Cloudy
30	2023-10-12 00:00:00	26	7.8	Cloudy
31	2023-10-13 00:00:00	25.8	7.6	Cloudy
32	2023-10-14 00:00:00	25.1	7.7	Cloudy
33	2023-10-15 00:00:00	25.1	7.6	Cloudy
34	2023-10-16 00:00:00	24.4	7.6	Cloudy
35	2023-10-17 00:00:00	23.7	7.5	Raining
36	2023-10-18 00:00:00	24.4	7.8	Cloudy
37	2023-10-19 00:00:00	24.6	7.5	Cloudy
38	2023-10-20 00:00:00	25	7.6	Cloudy
39	2023-10-21 00:00:00	24.9	7.9	Cloudy
40	2023-10-22 00:00:00	24	7.3	Cloudy
41	2023-10-23 00:00:00	23.9	7.3	Raining
42	2023-10-24 00:00:00	23.5	7.7	Raining
43	2023-10-25 00:00:00	23.2	7.3	Raining
44	2023-10-26 00:00:00	22.9	7.9	Raining
45	2023-10-27 00:00:00	24.7	7.4	Cloudy
46	2023-10-28 00:00:00	23.3	7.3	Raining

Figure 28 Weather conditions in Experiment 2

From figure 28, the weather conditions were mostly cloudy or rainy during the data collection for setup 2, with room temperature and natural light. The temperature is gradually dropping as there is not enough natural light shining on the leafy greens. This resulted in a slow pace of growth for the plant, but the pH value remains quite consistent. On October 17, rain was observed to pour downwards for the entire day continuously. The temperature dropped as low as 23 degrees, which means that the plant will not be able to grow much as there is no light for photosynthesis. Hence, external factors such as weather will affect the raw data collected by the IoT system. This shows that natural light is not a consistent food resource for the plant as the light varies depending on the changes in the weather.

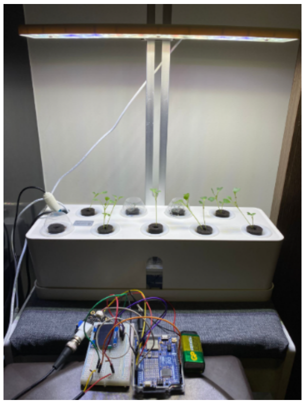


Figure 29 Third experiment

Similarly, to experiment 1 and 2, the seeds were put into the sponge soil and partially submerged in water over a span of 3 weeks as shown in figure 29. Caps were placed onto the plant to help contain the moisture and prevent algae growth in the initial stages. However, it can be noticed that more water vapor is being traps at the surface of the caps which may block the seeds from absorbing the LED light. After a while, the caps were removed to allow the *kale* to grow upright. Also, raw data of number of leaves, stem thickness, and length of the roots are taken down to give the user the growth conditions of the plants. The various stages are shown below in Figure 30.

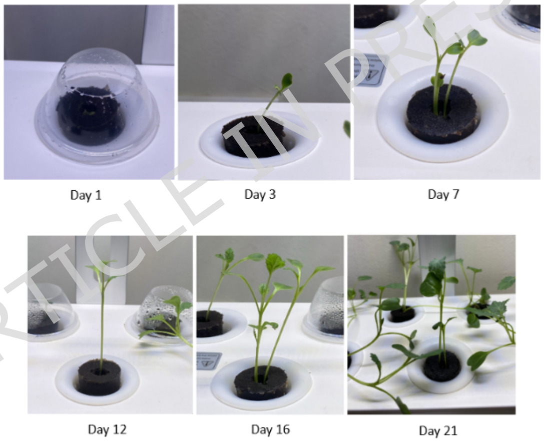


Figure 30 Stages of growth for Experiment 3

At the initial stage for day 1 to day 2, the *kale* seeds start to sprout. It can be noticed that some are still in seedlings even after 4 days. After 5-7 days, most seeds sprouted, and roots started growing out to the bottom, indicating that they were growing healthy. From day 14 onwards, the leafy greens grew at a fast pace, the leaves colour was light green, and the stem were growing upright. There be a change of water at day 14 to prevent growth of algae which will affect the growth of the leafy greens. The middle of the plants seems to grow upright while the sides are slanted, this can be cause by the light intensity of the LED light at the centre is the highest. Nevertheless, the remaining 7-21 days, the plants are left alone and monitored by the IoT system to see whether there are any drastic changes as seen in figure 30. It can be indicated that using LED lights, the plants seem to grow faster as compared to natural light as there is no external factors like weather.

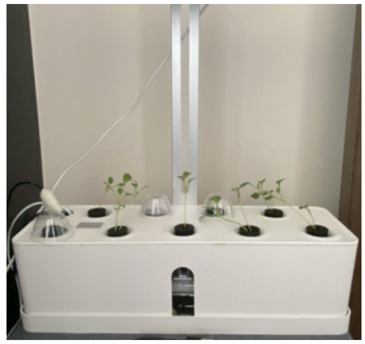


Figure 31 experiment 4

The setup above in figure 31 take place in a household environment at air-con temperature of 22 to 24 degree with natural light. For day 1 to day 5, the *kale* seeds only started to sprout. After 5 days, some of the holes are still in seedlings. After 5-7 days, most seeds have sprouted, and roots started growing out to the bottom, indicating that it was growing upright. From day 14 onwards, the leafy greens grew at a slow rate, the leaves colour was light green, and the stem were growing. To prevent growth of bacterial, there be a change of water at day 14 for new nutrients for the plant to take in. The plants are slanted to one direction, this must be where the sunlight is the brightest. Nevertheless, the remaining 7-21 days, the plants are left alone and monitored by the IoT system to see whether there are any drastic changes. It can be indicated that using natural light and air-con temperature, the plants seem to grow at the slowest rate as the weather is not constant.

46	2023-10-28 00:00:00	23.3	7.3	Raining
47	2023-10-29 00:00:00	23.3	7.8	Raining
48	2023-10-30 00:00:00	22.8	7.7	Raining
49	2023-10-31 00:00:00	23.7	7.8	Raining
50	2023-11-01 00:00:00	22.4	7.6	Raining
51	2023-11-02 00:00:00	23	7.3	Raining
52	2023-11-03 00:00:00	22.6	7.9	Raining
53	2023-11-04 00:00:00	23.1	7.5	Raining
54	2023-11-05 00:00:00	22.5	7.7	Raining
55	2023-11-06 00:00:00	22.1	7.7	Raining
56	2023-11-07 00:00:00	22.6	7.5	Raining
57	2023-11-08 00:00:00	22.7	7.6	Raining
58	2023-11-09 00:00:00	22.4	7.7	Raining
59	2023-11-10 00:00:00	22.5	7.5	Raining
60	2023-11-11 00:00:00	22	7.2	Raining
61	2023-11-12 00:00:00	22	7.5	Raining
62	2023-11-13 00:00:00	22	7.7	Raining
63	2023-11-14 00:00:00	22	7.3	Raining
64	2023-11-15 00:00:00	22	7.5	Raining

Figure 32 Weather conditions in Experiment 4

From above figure 32, the weather conditions were rainy during the data collection for setup 4, with air-con temperature and natural light. The temperature is gradually dropping as there is not enough natural light for the leafy greens. This resulted in a slow pace of growth for the plant, but the pH value remains quite consistent. Lastly, this implies that natural light is not a consistent food resource for the plant as the light varies depending on the changes in the weather which will affect the data collected by the IoT system. Natural lights are subjected to changes depending on the weather; the setup takes place from October to November, marking the start of Singapore's monsoon season. This meant that the plants were undergoing adverse temperature changes during each day. It will have subjected the plants to sudden changes in temperature and light intensity from natural light.

Discussions:

Discussion of Light temperature

In the beginning, it was crucial to introduce IoT technology to observe and control the impacts of light on the water temperature as shown in Figure 33. The DS18B20 water temperature sensor helped get the required procedures done in an appropriate time, as it was able to display the necessary information. For instance, should there arise a situation where the water temperature has increased due to high-light intensity to an unacceptable level, then the necessary steps would be to either decrease the light exposure or cool down the water. From figure 34, it reflects values of the temperature using IoT in hydroponic systems where UV light, temperature and other factors are maintained at optimum levels for plants to thrive.

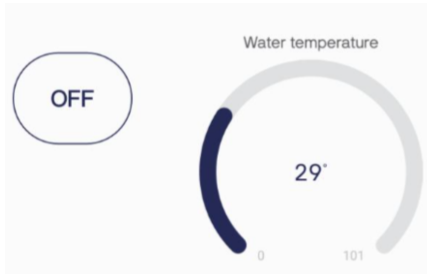


Figure 33 Water temperature monitor

The figure 34 below introduced the glaring differences in water temperature and its effect on plant growth in the four experimental setups. As each experiment takes place for 21 days, temperature changes will occur throughout the growth of the plants. There are a few changes to the temperature for the first experiment, which was room temperature with LED lights. The following setup with room temperature and natural lights has slight changes as the light received each day is dependent on the weather conditions in Singapore.

Figure 34 Water temperature graph

However, on November 22 there was a drastic drop in water temperature as shown in the graph. This may be due to the weather condition on that day, as it was raining the entire day which heavily affected the water temperature of the last experiment. Upon comparison, it is evident that LED lights are not just more energy efficient, but they also mean that the water temperature are able to remain in check for the plants to grow best as these exposed the plants to controlled conditions.

Table 3 Number of leaves

Days	Room Temp + LED Lights	Room Temp + Natural Lights	Air-Con + LED lights	Air-Con + Natural Lights
0	0	0	0	0
3	2	1	1	0
10	5	3	3	2
14	8	5	5	4
17	10	8	7	6
21	14	10	11	8

Based on Table 3, it illustrates the average leaf count of *kale* plants across four experimental setups over a 21-day period. The highest leaf count was observed in Setup 1 (Room Temperature + LED Light), with an average of 11.6 leaves, compared to 9.3 in Setup 2 (Room Temp + Natural Light), 8.4 in Setup 3 (Air-Conditioned + LED), and 7.2 in Setup 4 (Air-Conditioned + Natural Light). Leaf counting was performed manually every 3–4 days. Only fully emerged leaves greater than 1 cm in length were included in the count to ensure consistency. Experiments 1 and 4 use LED light to offer more control on the water temperature over time, resulting in an increased of number of leaves as compared to natural lightning. Experiments 2 and 4 have lesser-grown leaves, as the amount of natural light it received is very inconsistent. As the amount of natural light heavily depends on the availability of sunlight, which may fluctuate throughout the day. Especially during November in Singapore, as it is in the monsoon season, which causes the weather to be rainy throughout the month. By comparing the number of leaves, LED is more efficient and faster in growing leaves and plants.

In conclusion, arrangement 1 performed 61.1% better quantitatively than the worst-case arrangement 4, demonstrating the potently beneficial effects of artificial lighting and regulated temperature on photosynthesis and leaf development. According to this pattern, steady room temperatures combined with regular LED exposure produce the ideal environment for vegetative development. On the other hand, Setup 4's poorest performance might be the result of lower ambient temperatures and less light, which might restrict metabolic activity and postpone leaf start. These outcomes are consistent with research in Brito[14] that found that warm LED settings increased biomass accumulation.

Impact of Light intensities

In this experiment, monitored parameters with higher light intensities, particularly those using LED lights, showed a noticeable increase in water temperature compared to setups relying on natural light. Full-spectrum white LED grow lights were chosen for this experiment in order to replicate natural sunshine and promote photosynthesis in all plant pigments. The recommended are lights in the 400–700 nm in photosynthetically active radiation range are best for growing vegetables inside, particularly leafy greens like *kale*. This range is usually covered by white LEDs, which are appropriate for vegetative growth and have a corresponding color temperature of 4000–6500K. At a height of 28 cm, the lights employed in this study have a moderate intensity of about 300 µmol/m²/s, operating at 12 watts. This is within the recommended range of 200 to 400 µmol/m²/s for indoor leafy greens. To replicate a full day cycle, a photoperiod consisting of 16 hours of light and 8 hours of darkness was maintained. Sunrise and sunset were simulated by means of modest brightness changes. This approach aligns with best practices found in grow light literature for maximizing photosynthetic efficiency and ensuring robust, uniform plant development indoors. A study done by Brito shows that the light intensity of diverse types of LED light colour will have a direct effect on water temperature in hydroponic systems.

Table 4 Several types of LED lights [14]

Colour	Wavelength (nm)	Light intensity (lux)
Blue	450-495	20,000-40,000
Red	620-750	10,000-30,000
Green	495-570	2,000-10,000
White	400-700	25,000-50,000
Far-Red	700-800	5,000-15,000
UV (Ultraviolet)	<400	1,000-5,000
Infrared (IR)	>800	<5,000

5.

The data in Table 4 indicates that the light intensity of LEDs varies widely depending on their color, with white LEDs resulting in the highest intensity (25,000-50,000 lux) and infrared LED yielding the lowest intensity (<5000 lux). Stronger light intensities like that of blue and white LED mean more energy in the form of heat is transferred to the water causing the water temperature to rise. This increase in temperature may render the conditions for the plant roots sub optimal for effective nutrient uptake and growth of the plant as well [14]. However, green, or far-red LEDs, which have lower heat output, can prevent higher rise in the water temperature but may affect photosynthesis as the light intensity is exceptionally low. The results tell us that blue and red-LED of high intensity are excellent for photosynthetic processes, but the heat generated is likely to be detrimental to the roots [15]. Therefore, the color selection or the use of dimmable LEDs is promising in ensuring optimal water temperature while providing an adequate amount of light energy for photosynthesis.

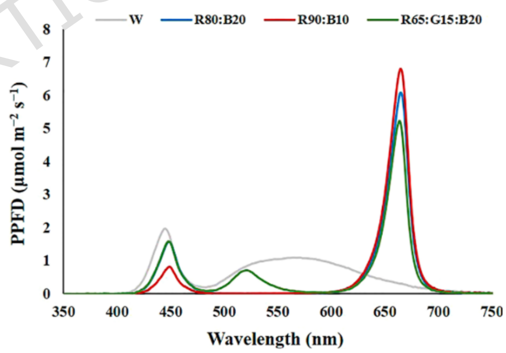


Figure 35 Wavelength of LED lights [14]

Ultimately, based on Figure 35, white LED light proves to be the most optimal choice for hydroponic systems due to its ability to mimic natural sunlight, which is also white in colour. White light contains a balanced spectrum of all visible wavelengths, providing a comprehensive energy source for photosynthesis across various plant pigments. Lastly, white LEDs also deliver high light intensity (25,000-50,000 lux), supporting robust plant growth while evenly distributing energy across the spectrum in the experiments.

Discussions of pH value

Using the IoT system, the pH analog sensor helped get the required data at an appropriate time and was able to display the necessary information on the Blynk application. Should there arise a situation where the pH value has increased to an unacceptable level, then the necessary steps would be to either decrease the light exposure or cool down the water. Figure 36 reflects values of the pH using IoT in hydroponic systems where UV light, temperature and other factors are maintained at optimum levels for plants to thrive.

Figure 36 pH value monitor

From the four experiment setups, figure 37 shows the fluctuation in pH value throughout and how it affects plant growth. To maintain consistency, each experiment was carried out for 21 days. In the first experiment, using room temperature and LED lights, there was a gradual increase in pH value due to biochemical reactions in the water. For example, higher temperatures caused by using LED lights speed up reactions that release hydrogen ions into the solution. Warmer water will cause critical nutrients like iron and phosphorus to become less available for the plants. All the essential micronutrients were changed and resulting in an increase of pH value.

Figure 37 pH value graph.

The second setup, with monitored parameters and natural lights, has slight changes except for a sudden drop on November 1. This is due to the changing of water every 2 weeks to prevent algae growth and new bacterial to maximise the growth of the leafy greens. For the third setup, the air-con room with LED lights, the pH value reached as high as 9 on November 22. This may be due to the low temperature, which leads to fewer hydrogen ion concentrations, which increases the pH value. It can be noticed that the water turns brown in colour, which indicates that algae is growing in the water, which makes the water acidic. Lastly, in the fourth setup in the air-con room and natural lights, there was a gradual increase in pH value, but everything remained the same. However, it can be noticed that the growth of the plants is extremely slow as compared to other experiments.
The data, summarized in Figure 37, show that optimal pH levels for *kale* cultivation were maintained between 7 and 8.5 in the best-performing setups in 1 and 2. However, Setups 3 and 4 showed greater pH fluctuations, with readings dropping to 7 on several occasions, likely

due to less nutrient uptake in cooler conditions, which may have disrupted the water chemistry.

In hydroponic systems, maintaining a constant pH is essential since drastic variations can impact plant root activity and nutrient solubility. Plant growth may be hampered by the reduced availability of minerals like calcium and magnesium at lower pH values that reach acidic levels. On the other hand, extremely alkaline levels may decrease iron and phosphorus absorption. While the less stable conditions in Setups 3 and 4 points to the necessity of automatic pH management, such as dosing pumps, in future designs, the controlled environment in Setups 1 and 2 helped buffer these fluctuations. All things considered, the findings emphasize how crucial it is to monitor pH in real time and control light levels in order to maximize plant health in IoT-enabled hydroponic systems.

Table 5 *Length of the roots*

Days	Room Temp + LED Lights	Room Temp + Natural Lights	Air-Con + LED lights	Air-Con + Natural Lights
0	0	0	0	0
3	2	1	1	0
10	4	2	3	1
14	6	4	5	3
17	9	6	7	5
21	12	9	10	8

Based on Table 5 above, experiments 1 and 2 maintain a pH value of 7 to 8, resulting in an increase in the length of roots as compared to experiments 3 and 4, as the ideal pH range for *kale* is 7 to 8, which allows the roots to absorb essential nutrients to promote root elongation. Meanwhile, experiments 3 and 4 have high pH values above the optimal range for *kale*. This will sunt the root growth as less nutrient is being absorbed into the plants and visible signs like the browning of colour which was displayed when changing of water. Root growth was measured manually by carefully removing the *kale* plants from the grow baskets at weekly intervals and measuring the longest root length with a calibrated ruler.

Table 6 *Length of stems*

Days	Room Temp + LED Lights	Room Temp + Natural Lights	Air-Con + LED lights	Air-Con + Natural Lights
0	0	0	0	0
3	0.5 – 1.0	0.3 – 0.8	0.5 – 1.0	0.3 – 0.5
10	2.0 – 4.0	0.8 – 2.0	1.0 – 1.5	0.5 – 1.0
14	4.0 – 6.0	2.0 – 4.0	1.5 – 3.0	1.0 – 1.8
17	6.0 – 8.0	4.0 – 6.0	3.0 – 5.0	1.8 – 3.5
21	8.0 – 10.0	6.0 – 8.0	5.0 – 7.0	3.5 – 5.5

From Table 6 above, monitored parameters from the experiments in a room temperature have a longer stem than the Air-con temperature. Using Figure 35, the best optimal range for pH value falls on both experiments 1 and 2 which provides nutrients like protein and chlorophyll to support cell division and stem elongation. The experiment 3 and 4, both have high pH value which will slow down photosynthesis and protein synthesis, resulting in shorter stems.

Impact of Algae growth

In this experiment, setups with higher pH value, particularly in air-con temperature, showed a noticeable increase in pH value as compared to setups in room temperature. This is attributed to the heat generated by the light source and room temperature on the water. A study done by Stephens shows the distinct types of Algae in the water will have a direct effect on the pH value which affect the water temperature in hydroponic systems.

Table 7 Different types of Algae in hydroponic system [16]

Algae types	Impact on pH value	Effects	Solutions
Green Algae	Causes pH fluctuations (higher during the day, lower at night)	Photosynthesis raises pH by producing oxygen during the day, while respiration at night lowers it	Reduce light exposure, use opaque covers, and apply algae inhibitors
Cyanobacteria	Raises pH significantly;	Produces substances that increase alkalinity	Control nutrient levels, minimize standing water, and ensure proper aeration
Brown Algae	Slightly lowers pH over time due to organic decay and nutrient depletion	Organic decay releases acidic compounds, and competition for nutrients can impact water chemistry	Regular cleaning, use of algae-preventive treatments, and maintenance of optimal nutrient balance
Black Algae	May lead to slight pH changes by consuming nutrients and releasing organic byproducts	Thrives in warm, poorly filtered water; releases substances that indirectly affect pH	Improve filtration, maintain optimal temperature, and manually remove colonies where feasible

From Table 7 above, algae in hydroponic systems increase or decreases the pH of water in such a way that it will hinder plants' health and growth. For instance, green algae are common in systems with a high amount of sunlight. Their use of light for photosynthesis during the day increases pH by releasing oxygen, whereas respiration at night decreases it. If nothing is done to prevent this variation, plants will suffer stress and have difficulty getting the nutrients they require. One method for addressing this issue is preventing excessive light or use of covers and algae inhibitors which would help in preventing algal growth [16]. In contrast, the longer brown algae are present, the more nutrients deplete and organic materials decay over time which prevent nutrient balance in the system and subsequently lower the pH value. This will result in higher water acidity levels which would worsen the balance of nutrients within the system. It is imperative that routine maintenance and precautionary measures be used to preserve the water in a health state [17]. Since during my experiment 3, there was brown algae overserved in the water which affected the pH value and resulted in the lowest temperature recorded of 21 degrees. There should be regular cleaning of the set up or maintenance of optimal nutrient balance. It becomes evident that managing algae growth is crucial for maintaining a stable pH and ensuring the hydroponic system's efficiency[17-19] and the health of the plants.

Comparative Evaluation with Existing Systems

Table 8 Comparative Analysis Between Present Study and Recent Works on IoT-Enabled Hydroponic

Case Study	Control Parameters	Sensors Used	IoT/Automation Features	Plant Type	Key Outcome
This study	pH, Temperature	pH sensor, DS18B20	Arduino UNO WiFi, Blynk Dashboard	*Kale*	15–20% higher growth under LED + room temp; stable pH between 6.5–7.0

Dey & Halder[21] (2025)	Temperature, Nutrients	DHT11, EC Sensor	NodeMCU, ThingSpeak	Lettuce	Stable temperature, basic automation without real-time control
Parab et al.[20] (2025)	Nutrients, Light	TDS, LDR, Temp	Raspberry Pi, App-based interface	Microgreens	Improved water and nutrient efficiency, no pH monitoring
Sharma et al.[19] (2025)	Temperature, Humidity (RH)	DHT22, Soil Moisture	Cloud-IoT (Firebase), Auto Fans	Tomato	Good for greenhouse but not tailored for indoor hydroponics

Table 8 illustrates how the current study combines monitored parameters in a small, Internet of Things-enabled home hydroponic prototype, setting it apart from more recent studies that frequently use non-real-time feedback or use another method instead of pH sensing altogether. Although Dey and Halder and Parab et al. concentrate on environmental sensing and nutritional automation, their systems do not integrate temperature and pH with cloud-based monitoring. Furthermore, under ideal lighting and environmental conditions, this study shows improved growth rates of leafy greens. By comparing all the key outcome of different case study's, it helps to determine the best alternative for sustainable urban farming.

Limitations of study

Although this study effectively illustrates how to grow leafy greens in a variety of environmental circumstances using monitored parameters in an IoT-enabled hydroponic system. There have been a number of drawbacks when collecting data and keeping the different experiments to be consistent and fair. First, the sensor suits only measures temperature and pH; important variables like light intensity and nutrient concentration (TDS/EC) were not directly assessed, which may compromise environmental control accuracy. Second, the manual nature of nutrient dosing may have limited the automation capability of the system and introduced minor variations among setups. Third, the environmental data sampling frequency was comparatively low, which would have missed transient variations that could affect plant reactions. This version does not have closed-loop feedback for temperature control or nutrient balancing, even if future work suggests real-time monitoring and control. Furthermore, only the early growth phase of *kale* was captured by the 21-day experiment duration, and the small sample size per setup may have affected creditability. There is also human error when taking the values of the experiment manually because of parallel error as the eye level is not at the same level as the measurement line. Lastly, the monitored parameters were evaluated in a controlled indoor setting; real-world variables, such as varying lighting conditions and outside temperature influences, which may cause different outcomes. Additional sensors, real-time data collection, and larger experimental designs will be used in subsequent generations to overcome these limitations. Due to the limited number of samples in this feasibility study, only average values were reported. We acknowledge the lack of statistical testing as a limitation. In future work, larger sample sizes and statistical analyses (ANOVA, standard deviation, and significance testing) will be employed to ensure rigor and reproducibility.

Our research work is classified as a “smart hydroponic” approach primarily due to its integration of IoT connectivity with real-time monitoring and partial automation. Specifically, the Arduino UNO WiFi continuously transmits water temperature and pH data to a cloud-based dashboard, allowing users to remotely track crop conditions and receive alerts when values deviate from optimal ranges, thus reducing the need for manual oversight. Additionally, we have programmed control of the LED photoperiod and water pump operation which will ensure consistent exposure and circulation without user intervention. While full adaptive feedback control of nutrient dosing and temperature is planned in future enhancements, the current prototype establishes the essential digital infrastructure and automated control elements that justify its classification as a smart hydroponic system.

Conclusion:

The initial phase includes determining the basic design requirements and characteristics for a household hydroponic that is integrated with IoT. This also entails the comprehension of user requirements and the selection of fundamental features such as real-time monitoring, automation, and connectivity. Other considerations that help support the premise of optimal growth include water temperature, light intensity, and nutrient levels. Once these requirements are established, the phase of design concentrates on transforming them into concrete parameters that include proper selection of sensors, hardware components, and software applications towards the achievement of sustainability, efficiency and usability aims of the system. Once the specifications are established, the next phase entails designing the IoT circuit to be able to understand and sense environmental variables such as light intensity and water temperature. This includes the combination of appropriate sensors, microcontrollers and connectivity modules to facilitate data collection and processing. After the circuit has been designed, a prototype is constructed in accordance with the specified parameters about the designed parameters with the integrative components of hardware configuration and programming. The prototype produced is therefore valid as it can demonstrate how the system works. The final phase involves evaluating the prototype's performance to ensure it meets the desired objectives. The monitored parameters system is tested under various conditions to assess its accuracy, reliability, and efficiency in maintaining optimal growing environments. Feedback from the evaluation process is used to identify areas for improvement refining the design and functionality. This ensures the system is robust, user-friendly, and effective for sustainable household hydroponics. All the objectives have been successfully achieved. Hence the aims of the present project had been successfully achieved.

Unlike previous domestic hydroponic or IoT-based urban agriculture systems, which often focus on a single parameter, lack real-time visibility, or rely heavily on manual intervention, our work presents a low-cost and fully networked household hydroponic prototype that simultaneously integrates continuous monitoring of both pH and water temperature with cloud-based data visualization and automated control of lighting and water circulation. This combination enables more consistent environmental control, remote oversight, and data-driven decision-making for users in compact indoor settings. Additionally, we provide a comparative performance study across four realistic home-farming scenarios, generating new empirical insights on how lighting source and ambient temperature affect kale growth in a domestic IoT-enabled hydroponic environment. These advancements represent the original contribution and strengthen the relevance and novelty of our research work.

Future works:

The current prototype does not measure nutrient concentration directly, but it does track pH levels as an indirect indicator of nutritional availability. In future work, the system should incorporate an Electrical Conductivity (EC) or Total Dissolved Solids (TDS) sensor to improve fertilizer control and automate hydroponic levels. By giving real-time data on nutrient content, these sensors can make sure the solution stays within ideal ranges (for example, 800–1200 ppm for *kale*). Technology could create a closed-loop nutrition delivery system by automatically correcting nutrient imbalances based on data gathered by sensor input to send to cloud platform. Particularly for long-term or commercial-scale indoor farming applications, this feature would greatly increase the smart hydroponic setup's accuracy, automation, and dependability. Due to data logging being done at a set daily timestamp (00:00), this study might not have captured the monitored parameters. In hydroponic systems, these variations can have a major effect on photosynthetic activity and nutrient uptake. Future studies should increase the sampling frequency, ideally logging sensor data every 15 to 60 minutes, to enhance data accuracy and system responsiveness. Better temporal resolution, statistical analysis of daily averages and trends, and automatic feedback control. The performance and accuracy of the IoT-enabled hydroponic system will be greatly increased by using the wide range of data sets being collected. Furthermore, we will incorporate a dedicated light intensity sensor as well to measure the light intensity and also a BH1750 Lux sensor to provide real-time light intensity data.

Proposed Automation Framework for smart hydroponics

To enhance the practical application of the IoT-enabled hydroponic system in future work, this study proposes a fully automated smart hydroponics framework that integrates real-time monitoring in a closed-loop control. The core of the system would rely on multiple sensors including a water temperature sensor (DS18B20), an analog pH sensor, a light intensity sensor (such as the BH1750), and a Total Dissolved Solids (TDS) or Electrical Conductivity (EC) sensor. These sensors would continuously monitor key environmental variables critical to plant health, such as nutrient concentration, water temperature, and light availability. The control system which is powered by a microcontroller like the Arduino UNO WiFi or ESP32 would send readings to the cloud which will inform the user if anything goes wrong. For instance, peristaltic dosing pumps can be used to add nutrient solutions A and B or pH buffers when deviations from the optimal range are detected. Similarly, an LED lighting controller would regulate the daily light cycle by mimicking natural photo periods like gradual sunrise and sunset. In the case of temperature fluctuations, a cooling fan or water chiller could be activated if the water temperature exceeds the ideal range of 28 degrees for leafy greens. The hydroponic system can be programmed to evaluate sensor data at regular intervals of 15 minutes and trigger specific actions accordingly. For example, if the pH value rises above 7.0, the system could dispense a mild acid buffer to restore balance; if the EC value drops below a predefined threshold, additional nutrients would be added. This dynamic adjustment would ensure that the plants receive optimal growing conditions without the need for constant manual intervention. This proposed framework transforms the current prototype into a comprehensive and scalable solution that supports sustainable, self-regulating urban farming. Future implementation and testing of this automated system would significantly improve reliability, yield consistency, and user accessibility in household hydroponic cultivation.

References

1. H. Shahab, M. Iqbal, A. Sohaib, F. Ullah Khan, and M. Waqas, "IoT-based agriculture management techniques for sustainable farming: A comprehensive review," *Computers and Electronics in Agriculture*, vol. 220, p. 108851, May 2024, DOI: 10.1016/j.compag.2024.108851.

2. S. Wei *et al.*, "Economic impacts of multiple natural disasters and agricultural adaptation measures on supply chains in China," *Journal of Cleaner Production*, vol. 418, p. 138095, Sep. 2023, DOI: 10.1016/j.jclepro.2023.138095.

3. C. M. Burt, A. J. Clemmens, R. Bliesner, J. L. Merriam, and L. Hardy, *Selection of irrigation methods for agriculture*. Reston, VA: American Society of Civil Engineers, 2000. DOI: 10.1061/9780784404621.

4. M. A. Rahman, N. R. Chakraborty, A. Sufiun, S. K. Banshal, and F. R. Tajnin, "An AIoT-based hydroponic system for crop recommendation and nutrient parameter monitorization," *Smart Agricultural Technology*, vol. 8, p. 100472, Aug. 2024, DOI: 10.1016/j.atech.2024.100472.

5. C. Prakash, L. P. Singh, A. Gupta, and S. K. Lohan, "Advancements in smart farming: A comprehensive review of IoT, wireless communication, sensors, and hardware for agricultural automation," *Sensors and Actuators A: Physical*, vol. 362, p. 114605, Nov. 2023, DOI: 10.1016/j.sna.2023.114605.

6. G. Ares, B. Ha, and S. R. Jaeger, "Consumer attitudes to vertical farming (Indoor plant factory with artificial lighting) in China, Singapore, UK, and USA: A multi-method study," *Food Research International*, vol. 150, p. 110811, Dec. 2021, DOI: 10.1016/j.foodres.2021.110811.

7. J. A. Diehl, E. Sweeney, B. Wong, C. S. Sia, H. Yao, and M. Prabhudesai, "Feeding cities: Singapore's approach to land use planning for urban agriculture," *Global Food Security*, vol. 26, p. 100377, Sep. 2020, DOI: 10.1016/j.gfs.2020.100377.

8. Singapore Food Agency "30 by 30." Accessed: Jun. 26, 2024. [Online]. Available: https://www.ourfoodfuture.gov.sg/30by30/

9. P. Gan, "9 urban farms in Singapore for locally-grown vegetables of high quality," TheSmartLocal - Singapore's Leading Travel and Lifestyle Portal. Accessed: Jun. 27, 2024. [Online]. Available: https://thesmartlocal.com/read/urban-farms/

10. "Tabletop hydroponics kit (Kit only)," Urban Green Dot. Accessed: Jul. 24, 2024. [Online]. Available: https://urbangreendot.sg/product/tabletop-hydroponics-kit/

11. R. Uchiyama, S. Yamaguchi and Y. Takahashi, "Solar Power Generation for Compact Hydroponic Plant Cultivation System," 2019 19th International Conference on Control, Automation and Systems (ICCAS), Jeju, Korea (South), 2019, pp. 827-832, doi: 10.23919/ICCAS47443.2019.8971554.

12. M. S. A. B. M. Ali, M. K. B. Nordin, M. H. B. M. Zaki and M. F. B. Saaid, "Optimizing Plant Growth in Indoor NFT Hydroponic Systems: Design, Environmental Monitoring, and Analysis," *2024 IEEE International Conference on Applied Electronics and Engineering (ICAEE)*, Shah Alam, Malaysia, 2024, pp. 1-6, doi: 10.1109/ICAEE62924.2024.10667552.

13. A. Yudhana and A. C. Kusuma, “Water quality monitoring at paddies farming based on android,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 403, p. 012042, Oct. 2018, DOI: 10.1088/1757-899X/403/1/012042.

14. C. Brito *et al.*, “Different LED light intensity and quality change perennial ryegrass (Lolium perenne L.) physiological and growth responses and water and energy consumption,” *Front. Plant Sci.*, vol. 14, p. 1160100, Apr. 2023, DOI: 10.3389/fpls.2023.1160100.

15. K. Kitazaki *et al.*, “Metabolic Reprogramming in Leaf Lettuce Grown Under Different Light Quality and Intensity Conditions Using Narrow-Band LEDs,” *Sci Rep*, vol. 8, no. 1, p. 7914, May 2018, DOI: 10.1038/s41598-018-25686-0

16. O. Stephens, “How to test the pH of water,” The Hydroponics Planet. Accessed: Dec. 08, 2024. [Online]. Available: https://thehydroponicsplanet.com/how-to-test-the-ph-of-water-complete-guide/

17. A. Jamie, “Learn to adjust ph and ec in hydroponics for ideal conditions.” Accessed: Dec. 08, 2024. [Online]. Available: https://whyfarmit.com/hydroponic-ph-and-ec/

18. A. Morchid *et al.*, "An Innovative Smart Irrigation Using Embedded and Regression-Based Machine Learning Technologies for Improving Water Security and Sustainability," in *IEEE Access*, vol. 13, pp. 100731-100751, 2025, DOI: 10.1109/ACCESS.2025.3577911

19. Morchid, A., Et-taibi, B., El Alami, R., Abid, M.R., Boufounas, EM. (2025). Internet of Things (IoT)-Based Sustainable Agriculture: A Smart Irrigation System Using Embedded System and WebSockets. In: Elsadany, A.A., Adel, W., Sabbar, Y. (eds) Biology and Sustainable Development Goals. Mathematics for Sustainable Developments. Springer, Singapore. https://doi.org/10.1007/978-981-96-3094-3_10

20. A. Morchid, Z. Said, A. Y. Abdelaziz, P. Siano, and H. Qjidaa, “Fuzzy logic-based IoT system for optimizing irrigation with cloud computing: Enhancing water sustainability in smart agriculture,” *Smart Agricultural Technology*, vol. 11, p. 100979, Aug. 2025, DOI: 10.1016/j.atech.2025.100979

21. A. Morchid, B. Et-taibi, R. El Alami, M. R. Abid, and E.-M. Boufounas, “Internet of Things (IoT)-Based Sustainable Agriculture: A Smart Irrigation System Using Embedded System and WebSockets,” in *Biology and Sustainable Development Goals*, A. A. Elsadany, W. Adel, and Y. Sabbar, Eds., Singapore: Springer Nature Singapore, 2025, pp. 243–254. DOI: 10.1007/978-981-96-3094-3_10

22. Don Chua, W.F.; Lim, C.L.; Koh, Y.Y.; Kok, C.L. A Novel IoT Photovoltaic-Powered Water Irrigation Control and Monitoring System for Sustainable City Farming. Electronics 2024, 13, 676. DOI: 10.3390/electronics13040676

Data Availability
All data generated or analyzed during this study are included in this published article.

Funding Declaration
There is no funding involved in this research work.

Declaration
The plant collection and use was in accordance with all the relevant guidelines