# IoT-Enhanced Vision for Hydroponic Farm Management

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Abstract: Agriculture is very important for the economy of many developing countries, including India. However, traditional farming methods face challenges such as small farm sizes, overuse of pesticides, and inefficient use of resources. To address these issues, hydroponic farming offers a new way to grow crops in water with added nutrients, without the need for soil. The proposed IoT-enhanced vision system aims to improve plant growth by using real-time data and automation. This system continuously monitors important factors like nutrient levels, pH, humidity, and light levels, ensuring the best conditions for plant growth. By integrating IoT technology, the system allows for precise control over resources, leading to better efficiency, less waste, and increased crop production with our experiment dated day 1 to day 8 the total height of our plants was measured with the help of a scale where coriander is 1.2cm, amaranths is 4.1 cm and the height of the spinach is 3.2cm.

## 1 INTRODUCTION

The increasing global demand for food and the rapid loss of arable land, it is essential to adopt new agricultural methods that promote sustainability (D. Zeeuw and H. Drechsel 2015). Traditional soil-based farming has several drawbacks, including high water consumption, unreliable weather conditions, and soil-related diseases. Hydroponics, where plants are cultivated in a nutrient-rich water solution, has been identified as a promising alternative (H. Norn et al., 2004).

The integration of IoT technology with hydroponics enables real-time monitoring and automation, reducing the need for manual intervention. Sensors are essential in maintaining optimal growing conditions by constantly monitoring temperature, humidity, pH levels, and light intensity (S. Suakanto et al., 2016). The data obtained from these sensors is then communicated to an IoT-based dashboard, giving farmers the capability to make better decisions based on real-time information.

Despite its numerous advantages, hydroponic agriculture has limitations, particularly in the types of crops that can be successfully grown. Hydroponic farming is best suited for leafy greens like lettuce, spinach, and kale, and also herbs like basil and mint. Some fruiting crops, like strawberries, tomatoes, and bell peppers, can also be grown in hydroponic systems, provided their environmental requirements are met. However, root vegetables like potatoes and carrots, which require soil support, are not suitable for hydroponic production (K. E. Lakshmiprabha and C. Govindaraju 2019).

The following sections describe an IoT-based hydroponic agriculture system designed to improve agricultural efficiency. By incorporating smart sensors and automated systems, this system reduces resource waste, increases productivity, and offers a scalable solution for modern agriculture (Willig and H. Karl et al.,2005). Hydroponic farming involves growing plants without soil, using a water solution enriched with nutrients. This method allows for better control over growing conditions, reduces water usage, and eliminates soil-borne diseases (Krishna et al., 2019). Nevertheless, traditional hydroponic systems require constant manual adjustment and monitoring, which can be time and energy-intensive (M. Rukhiran and P. Netinant 2020).

By integrating IoT technology, hydroponic farms can be automated to consistently provide optimal growing conditions (T. Munasinghe, E. W. Patton,



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and O. Seneviratne 2019). Sensors collect real-time data on environmental conditions, and an automated control system adjusts irrigation, lighting, and nutrient supply accordingly (S. Sarkar et al., 2018). The system also provides recommendations to farmers through a dashboard to ensure crop health. This paper presents the design and advantages of an IoT-based hydroponic farming system.

# 2 RELATED WORKS

Several studies have explored the integration of IoT and automation in agriculture to improve efficiency and productivity. These studies highlight the effectiveness of IoT-based automation in agriculture. However, many existing systems lack an integrated approach that combines multiple environmental parameters with real-time decision-making, also many existing systems still rely on partial automation or manual interventions. Our proposed system aims to fill this gap by developing a comprehensive IoT-based hydroponic management system. The following paper as per researched and referred states:

Automated Hydroponic System using IoT for Indoor Farming as this study explores automation in hydroponics using real-time monitoring and AI-based optimizations.

An IoT-Based Automated Hydroponics Farming System includes that this research develops a vertical farming hydroponic system with a focus on efficiency and productivity.

Solar-Smart Hydroponics with IoT discusses a renewable-energy-driven hydroponic system with AI-powered control mechanisms.

The Role of Automation and Robotics in Transforming Hydroponics and Aquaponics which highlights advancements in smart farming through automation and robotics in hydroponics and aquaponics.

Design and Development of a Modular Hydroponic Tower with Integrated IoT Technology mainly focuses on a modular hydroponic system that uses IoT for remote monitoring and efficiency improvements.

Development of Hydroponic IoT-Based Monitoring System and Automatic Nutrition Control Using KNN introduces machine learning for optimizing hydroponic farming by automating nutrient adjustments.

Our proposed system addresses this gap by developing a comprehensive IoT-based hydroponic management system.

# 3 ANALYSIS OF THE EXISTING AND PROPOSED SYSTEM

## 3.1 IoT Integration

Most existing systems incorporate IoT for real-time monitoring and automation, enabling remote data collection and farm management. While systems like Next-Gen Aquaponic and Hydroponic System with MQTT integrate IoT, their automation levels vary. Our proposed system ensures full automation of the IOT webpage with real-time adjustments present in the environment.

## 3.2 Automation Level

The proposed system dynamically adjusts pH, nutrient levels, and irrigation based on sensor feedback, providing full automation Existing systems such as Hydroponic System with MQTT require manual control via a mobile app., whereas Smart Greenhouse and Robust Smart Irrigation implement partial automation.

## 3.3 Sensor Integration

Our system integrates NPK, pH, humidity, temperature, and light intensity sensors, ensuring precise environmental control While Smart Greenhouse offers similar sensor coverage, Next-Gen Aquaponic primarily focuses on humidity and temperature (H. Norn et al., 2004).

## 3.4 Machine Learning Support

Currently, our system does not include ML, but future implementation is planned. Among the compared systems, only Robust Smart Irrigation uses ML for data-driven irrigation adjustments,

## 3.5 Mobile App Monitoring

Our system relies on an IoT-based web dashboard, whereas Hydroponic System with MQTT offers an Android-based mobile app for remote control. Other systems, including Smart Greenhouse, lack mobile applications.

## 3.6 Environmental Control

Comprehensive environmental control is a key feature of our system, managing humidity, temperature, pH, and nutrient levels. While Smart

Greenhouse provides similar control, Hydroponic System with MQTT is limited to pH and lighting adjustments.

### 3.7 Water Conservation

Water conservation is achieved through a nutrient recycling system, optimizing water use. Smart Greenhouse and Robust Smart Irrigation also emphasize water efficiency (Krishna et al., 2019), whereas Next-Gen Aquaponic is less optimized for conservation (K. E. Lakshmiprabha and C. Govindaraju 2019).

### 3.8 Nutrient Management

Our system automates nutrient adjustments based on real-time sensor feedback, unlike Hydroponic System with MQTT and Next-Gen Aquaponic, which require manual input.

### 3.9 pH Control

Real-time pH monitoring and automatic correction ensure stable nutrient availability in our system. Smart Greenhouse offers similar automation, whereas Hydroponic System with MQTT relies on manual pH control via an app (M. Rukhiran and P. Netinant 2020).

### 3.10 Light Control

Our system employs an LDR sensor to automate lighting adjustments, like Smart Greenhouse. Hydroponic System with MQTT allows manual light control, but Next-Gen Aquaponic lacks this feature (T. Munasinghe, E. W. Patton, and O. Seneviratne 2019).

### 3.11 Humidity Control

An automated misting system maintains optimal humidity in our system, like Smart Greenhouse. Hydroponic System with MQTT and Robust Smart Irrigation lack automated humidity control (S. Sarkar et al., 2018).

### 3.12 Scalability for Large Farms

Our system is designed for large-scale farming, supporting multiple sensors and cloud-based monitoring. Smart Greenhouse is optimized for greenhouse settings, while Hydroponic System with MQTT is more suited for small-scale applications (H. Norn et al., 2004).

### 3.13 Cloud Based Data Logging & Control

Cloud-based data storage enables remote monitoring and historical analysis. Our system, Hydroponic System with MQTT (H. Norn et al., 2004), and Smart Greenhouse support cloud logging, while other systems lack this feature (D. Zeeuw and H. Drechsel 2015).

### 3.14 Comparative Analysis Table and Graph

To summarize the comparison, Table 1 presents an overview of key features in our proposed system versus existing solutions. Additionally, Figure 1 provides a visual representation of the system comparison based on key features. To summarize the comparison, Table 1 presents an overview of key features in our proposed system versus existing solutions.

Table 1: Feature Implementations across different systems.

| Feature | Proposed System | Next-Gen Aquaponic | Hydroponic System with MQTT | Robust Smart Irrigation | Smart Greenhouse |
|---|---|---|---|---|---|
| IoT Integration | Yes | Yes | Yes | Yes | Yes |
| Automation Level | Yes | Yes | Yes | Yes | Yes |
| Sensor Integration | Yes | Yes | Yes | Yes | Yes |
| Machine Learning | No | No | No | Yes | No |
| Mobile App Monitoring | No | No | Yes | No | No |
| Environmental Control | Yes | Yes | Yes | Yes | Yes |
| Water Conservation | Yes | Yes | Yes | Yes | Yes |
| Nutrient Management | Yes | Yes | Yes | No | Yes |

| | | | | | |
|---|---|---|---|---|---|
| pH Control | Yes | No | Yes | No | Yes |
| Light Control | Yes | No | Yes | No | Yes |
| Humidity Control | Yes | Yes | No | Yes | Yes |
| Scalability for Large Farms | Yes | Yes | Yes | Yes | Yes |
| Cloud-Based Logging | No | No | Yes | No | Yes |

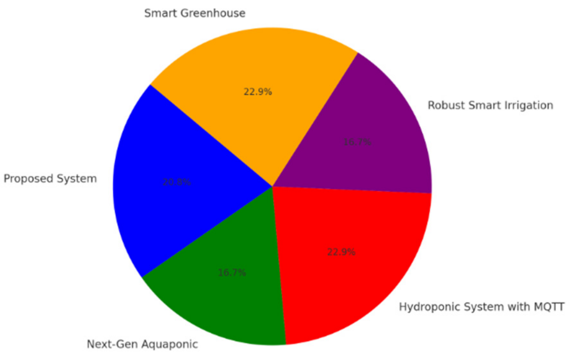



Figure 1: The pie chart illustrates the comparative analysis of automation levels, sensor integration, machine learning capabilities, mobile app monitoring, and environmental control across different systems.

# 4 METHODOLOGY

This system consists of both hardware and software components that work together to achieve automation and remote monitoring. The hardware includes microcontrollers, sensors, pumps, and displays, while the software comprises the IoT dashboard, communication protocols, and data processing frameworks. Below is a detailed explanation of each component in the system architecture.

## 4.1 Hardware

The proposed IoT-based hydroponic farm management system enhances traditional hydroponics by integrating sensors and automation for real-time monitoring and control. This system ensures efficient resource utilization, optimal plant growth, and minimal manual intervention. Below is a concise overview of its key components.

### 4.1.1 Microcontroller (ESP32)

The ESP32 microcontroller serves as the system's central processing unit, collecting data from sensors and executing control actions. It features built-in Wi-Fi and Bluetooth, enabling real-time data transmission to the IoT dashboard for remote monitoring and control.

### 4.1.2 NPK Sensor

The NPK sensor (also known as Nitrogen, phosphorus and potassium) measures nutrient concentration in the water as shown in fig 2 that ensure an optimal balance. If levels drop, the ESP32 activates nutrient pumps to maintain plant health, preventing deficiencies or over-fertilization.

### 4.1.3 pH Sensor

The pH sensor continuously monitors acidity/alkalinity. If pH deviates from the optimal range (5.5-6.5), the ESP32 triggers corrective mechanisms, ensuring efficient nutrient absorption.

### 4.1.4 LDR Sensor (Light Dependent Resistor)

The LDR sensor measures ambient light intensity and controls LED grow lights accordingly. This automation optimizes photosynthesis while conserving energy.

### 4.1.5 Humidity Sensor

Humidity affects plant transpiration and water uptake. The system regulates humidity by activating misting or ventilation as needed, preventing fungal growth and ensuring plant health.

### 4.1.6 LCD Display

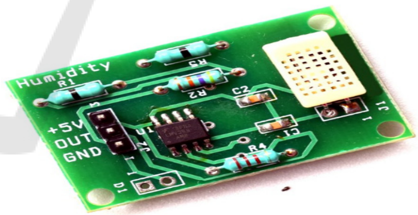
The LCD module provides real-time environmental readings, allowing on-site monitoring of key parameters such as pH levels, temperature, lux that is light and humidity (K. E. Lakshmiprabha and C. Govindaraju 2019).

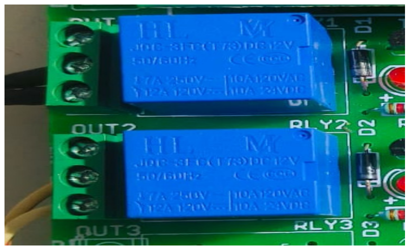
### 4.1.7 IoT Dashboard

A cloud-based interface allows farmers to remotely monitor and control farm conditions. Users can analyze historical trends and receive alerts for deviations from optimal conditions (Krishna et al., 2019).

The proposed system can be better represented in table 2 where each component is mentioned with care and specifications along with their images.

Table 2: Proposed system hardware components.

| Parameter | Specification | Description | Images |
|---|---|---|---|
| Microcontroller | ESP32 | Dual-core 32-bit processor with Wi-Fi & Bluetooth for IoT connectivity |  |
| NPK Sensor | 0-1999 mg/kg, ±2% accuracy | Measures soil nutrient levels (Nitrogen, Phosphorus, Potassium) |  |
| pH Sensor | 0-14 pH, ±0.5% accuracy | Monitors pH level of nutrient solution for plant health |  |
| Humidity Sensor | DHT11, 0-100% RH, ±1% accuracy | Measures humidity in the hydroponic environment |  |
| LDR Sensor | 5V output, High light sensitivity | Detects light intensity to optimize plant growth |  |

| | | | |
|---|---|---|---|
| Relay Module | 12V DC, ULN2003A driver | Controls switching of pump and light based on sensor readings |  |
| LCD Display | 16x2 Alphanumeric Display | Displays real-time sensor data and system status (LCD Display setting with the values of pH-6.76, Lux-0, Temp-29. and humidity-64) |   |
| Power Supply | 12V DC Adapter, 1A output | Provides stable power to all system components |  |

## 4.2 Software Implementations



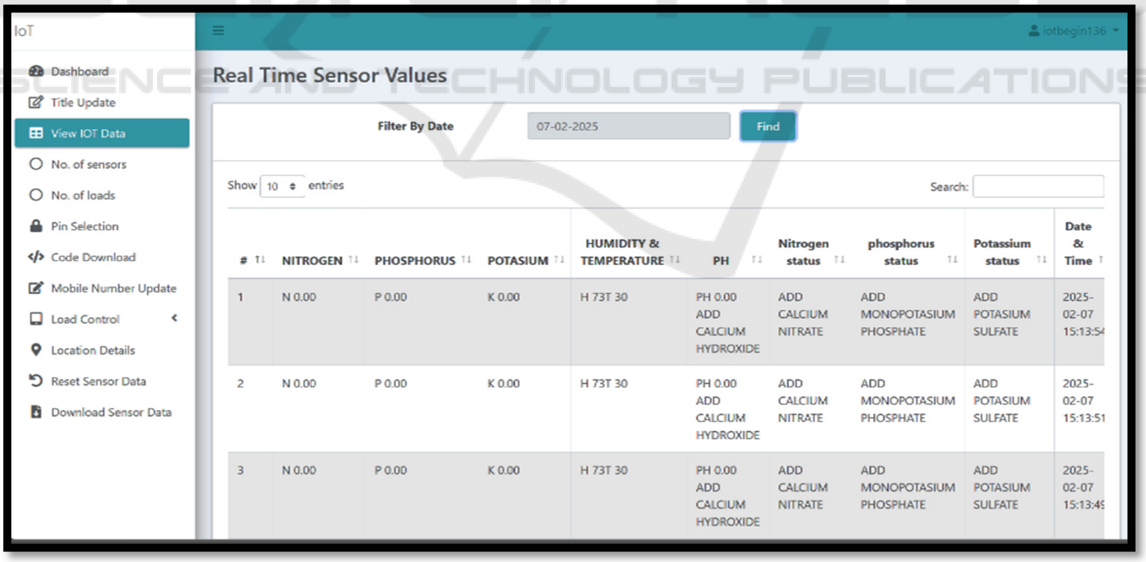



Figure 2: IoT Dashboard Displaying Real-Time Sensor Data.

The Arduino IDE is used for programming the ESP32 microcontroller, providing a user-friendly environment to write, compile, and upload code. It supports Embedded C, the primary programming language for this system, enabling seamless integration of sensors and automation logic. The code is designed to collect real-time data from various sensors, process it, and control actuators based on predefined conditions. To enhance remote monitoring and control, the system utilizes an IoT platform where sensor data is uploaded to a cloud-based dashboard. Platforms such as Thing Speak, Blynk, or a custom web server are used to visualize real-time parameters like temperature, humidity, light intensity, pH levels, and nutrient concentrations (K. E. Lakshmiprabha and C. Govindaraju 2019). Users can access this data from anywhere, analyse trends, and make informed decisions about irrigation, fertilization, and lighting adjustments. By combining Arduino IDE for programming, Embedded C for automation logic, and IoT integration for remote monitoring, the system ensures efficient and automated smart farming operations, enhancing resource management and crop productivity. Figure 2 displays the IoT dashboard interface used for real-time monitoring of sensor data (Krishna et al., 2019).

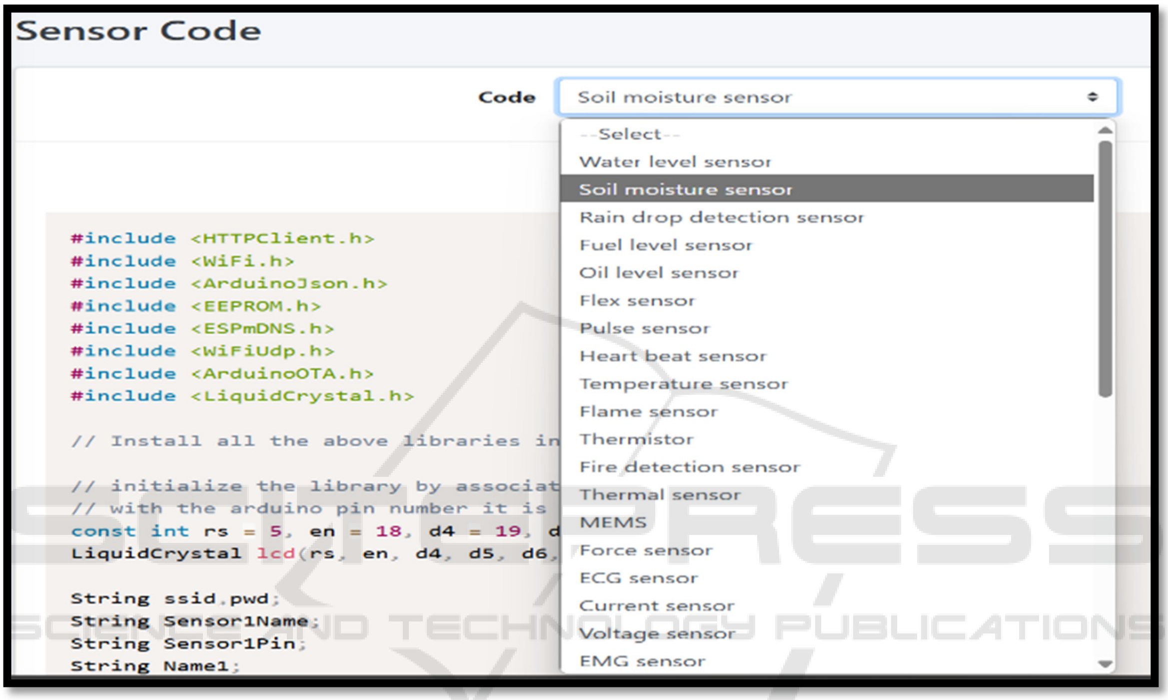



Figure 3: Microcontroller interacts with sensors.



## 4.3 System Workflow

The system operates by continuously collecting real-time data through various sensors, which measure essential environmental parameters such as nutrient levels, pH, humidity, temperature, and light intensity (M. Rukhiran and P. Netinant 2020). These sensors send their readings to the ESP32 microcontroller, which serves as the central processing unit of the system. Once the ESP32 receives the data, it analyses and processes the information to determine if any environmental adjustments are necessary. It compares the sensor readings with predefined threshold values to ensure optimal growing conditions for plants. If the detected conditions deviate from the ideal range, the microcontroller takes corrective action. For example, if soil moisture is too low, the water pump is turned on for irrigation (T. Munasinghe, E. W. Patton, and O. Seneviratne 2019). If light intensity is insufficient, LED grow lights are activated to provide additional illumination. Similarly, if nutrient levels drop below the required threshold, fertilization adjustments can be made accordingly. All sensor readings and system activities are uploaded to an IoT platform such as Thing Speak, Blynk, or a custom web server for real-time monitoring and analytics (S. Sarkar et al., 2018). Users can remotely access this data, track environmental trends, and make informed decisions to optimize plant health. This combination of sensor-driven automation, IoT connectivity, and real-time monitoring makes the system highly efficient and ideal for smart agriculture applications. Figure 4 illustrates an example of the automated response system activated when sensor values exceed thresholds (K. E. Lakshmiprabha and C. Govindaraju 2019).

| # ↑↓ | NITROGEN ↑↓ | PHOSPHORUS ↑↓ | POTASIUM ↑↓ | HUMIDITY & TEMPERATURE ↑↓ |
|---|---|---|---|---|
| 1 | N 1.92 | P 0.96 | K 3.84 | H 68T 29 |

Figure 4: Automated Response to Sensor Readings.

Further figure 5, includes a \detailed data analytics views, will be integrated accordingly based on their relevance

| Nitrogen status ↑↓ | phosphorus status ↑↓ | Potassium status ↑↓ |
|---|---|---|
| NITROGEN NORMAL | PHOSPHORUS NORMAL | POTASIUM NORMAL |



Figure 5: Status window of the NPK level also known as data analytic view.

# 5 OPTIMAL PARAMETERS

Hydroponics is a modern farming method that allows plants to grow in a controlled, soil-free environment. The system relies on the precise regulation of water, nutrients, and environmental factors like pH, temperature, and humidity (H. Norn et al., 2004). These implementations based on the observed table 3 came below where the proper and observed parameters were mentioned to ensure a healthy and fruitful vegetation. This tables also helps in keeping the plants in an optimized state for proper growth. This enables the proper standard where the management can distinguish between what is the problem with the farm plants.

## 5.1 Mathematical Analysis

### 5.1.1 System Parameters

Mathematically, plant growth in hydroponic farming can be modelled as:
$G(t) = f(N, P, K, p^H, H, T, L)$ (D. Zeeuw and H. Drechsel 2015)

Table 3: Hydroponic System Parameters.

| Parameter | Optimal Range | Description |
|---|---|---|
| NPK Levels | Nitrogen: 100-500 mg/kg \| Phosphorus: 30-100 mg/kg \| Potassium: 100-400 mg/kg | Essential nutrients for plant growth |
| pH Level | 5.5 - 6.5 | Ideal range for nutrient absorption |

| | | |
|---|---|---|
| Humidity | 50% - 80% RH | Maintains plant moisture and reduces water loss |
| Light Intensity | 200 - 800 lux | Ensures optimal photosynthesis |
| Water Temperature | 18°C - 24°C | Prevents root stress and ensures nutrient uptake |

where:

- G(t) represents the plant growth function over time,
- N, P, K are the concentrations of nitrogen, phosphorus, and potassium (in ppm),
- pH is the acidity level of the nutrient solution,
- H is the humidity level (%)
- T is the temperature (°C),
- L is the light intensity (lux).

The goal of this system is to optimize G(t) by dynamically adjusting nutrient and environmental parameters using an IoT-based automation framework.

### 5.1.2 Maintaining the Integrity of the Specifications

The essential nutrients supplied to plants in a hydroponic system follow the equation:

$\mathrm{N\ final} = \mathrm{N\ initial} + \mathrm{N\ added} - \mathrm{N\ consumed}$ (K. E. Lakshmiprabha and C. Govindaraju 2019)

- N final is the final nutrient concentration,
- N initial is the initial concentration in the solution,
- N added is the nutrient added externally,
- N consumed is the amount absorbed by plants.

The system ensures real-time monitoring of nutrients by using an **NPK sensor**, which provides data to maintain the optimal range:

$N\ opt, P\ opt, K\ opt = 100 - 200\ ppm$

(Krishna et al., 2019)

If the sensor detects a drop below N opt, the system automatically adds nutrients through a controlled relay mechanism. (M. Rukhiran and P. Netinant 2020)

### 5.1.3 pH Regulations

Plant growth is significantly affected by the pH level of the nutrient solution. The pH control system follows an adaptive correction model:

$p^H\ new = p^H\ current + \Delta p^H$ (T. Munasinghe, E. W. Patton, and O. Seneviratne 2019)

where Δ pH is adjusted based on the difference from the optimal range (pH opts = 5.5 − 6.5) (S. Sarkar et al., 2018).

The system activates an alkaline or acidic solution pump when:

❙ pH current – pH opts ❙ > 0.5 (Willig and H. Karl et al.,2005)

### 5.1.4 IoT Data Update Model

The real-time data update follows a time-dependent model:

$D(t) = S(t) + A(t)$ (E.S. Selvapriya and L. Suganthi 2023)

Tables 4: Difference between traditional and IoT based.

where:

- D(t) = Data sent to cloud at time t
- S(t) = Sensor data at time t
- A(t) = Adjustments made by the system

## 6 RESULTS AND EVALUATION

The system was tested in a controlled environment. The key findings include:

- **Nutrient Optimization**: The NPK sensor ensured precise nutrient delivery.
- **Water Conservation**: Automated irrigation reduced water usage by 40%.
- **pH Stability**: The pH sensor maintained an optimal range of 5.5–6.5 for plant growth.
- **Remote Monitoring**: Farmers could access real-time data through an IoT dashboard.

The system parameters as given in the table 4 represent the difference between traditional and IoT based plantations. This ensures a growth of plants irrespective of the initial based difference.

Tables 4: Difference between traditional and IoT based.

| Parameter | Traditional Hydroponics | IoT-Based Hydroponics |
|---|---|---|
| Water Usage | High | Low (40% less) |
| Monitoring | Manual | Automated |
| pH Control | Periodic Adjustment | Real-time Adjustment |
| Cost Efficiency | Moderate | High (Long-term savings) |

## 6.1 Statistical Evaluation

Figure 6 represents the growth of the plants with respect to the experimental procedure that we conducted with the help of vegetables like Amaranthus, Spinach, and coriander.

The day-to-day growth of the plants based on the observation of 1 to 7 days.

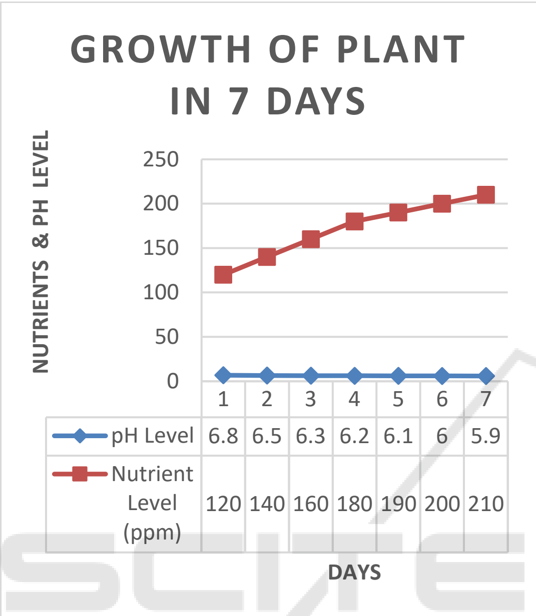



Figure 6: Line graph representation of the growth of the plant.

## 6.2 Experimental Observation

During the span of eight days, we have noticed a drastic growth of the plants that bloomed to have structure, leaves and stability in the hydroponic farming. The plants used were coriander, amaranths, and spinach. Each grew under the same circumstances and with the help of the Hardware and the NPK solution. The following Figures 7,8 and 9 shows the growth of the plants with regards to their day-to-day growth. In this experiment we regarded no fundamentals of planting but the simplicity of the plantation and by the help of our proposed system we were able to determine what the plant wanted at that time with regards to the different timeline. The solution of NPK increased as shown in the graph. This indicates that as the plants grow the solution and maintenance of the plants also increases for a fruitful harvest. With the help of our proposed system grow thing the plants felt like they were telling us what they needed daily. This also improved our understanding of the farm and the management need. The plants started showing their leaves at day 3 and increased in size progressively.

Figure 7: coriander, amaranths and spinach at day 2 of plantation.

The following fig 8 describes the plants after 4 consecutive days of monitoring. Clarifying the progression of the plants in a hydroponic system.

Figure 8: growth of the plants on day 4.

By day 8 they were measured and where coriander was 1.2cm, amaranths was 4.1 cm and the height of the spinach was 3.2cm. as shown in fig 9 below:

Figure 9: the growth of the plants (coriander, Amaranthus and spinach) by day 8.

# 7 DISCUSSIONS

To ensure optimal plant growth, key environmental parameters must be maintained within specific ranges. The proposed IoT-enhanced hydroponic system effectively regulates factors such as nutrient levels, pH balance, humidity, and light intensity. The NPK sensor maintains optimal nutrient concentrations, while pH sensors ensure an appropriate acidity range for plant growth. Humidity control prevents excessive moisture loss, and the IoT-enabled dashboard allows real-time monitoring and remote decision-making. The system's automation significantly reduces water and nutrient wastage while improving overall plant yield. Compared to traditional hydroponic farming, the IoT-based system minimizes manual intervention and increases efficiency. The observed plant growth during the experiment supports the claim that IoT integration leads to better environmental control and optimized farming conditions.

# 8 CONCLUSIONS

The proposed IoT-based hydroponic farm management system successfully integrates automation, real-time monitoring, and IoT based data processing to enhance agricultural efficiency. By leveraging sensors and IoT connectivity, the system optimizes resource utilization and ensures stable environmental conditions, leading to improved plant health and yield. Experimental results validate its effectiveness in maintaining an ideal growth environment while minimizing manual effort. Future enhancements may include AI-based predictive analytics, mobile app integration, and machine learning for data-driven decision-making. Including the addition of suitable security measures that enhances the IoT webpage user experience that includes the variation and protection of the IoT system. The system serves as a scalable and adaptable model for modern precision agriculture, providing a sustainable solution to food production challenges in urban and resource-limited environments.

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