

# Cloud-Integrated Automated Dosing System for pH and Nutrient Control in NFT Hydroponics Using ThingSpeak

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## Abstract

Hydroponics is a modern agricultural technique in which plants are cultivated in nutrient rich water instead of soil. With increasing urbanization and the reduction of fertile agricultural land in Nepal, there is a growing need for efficient and sustainable farming technologies. The study presents the design and implementation of a cloud-integrated automated dosing system for pH and nutrient control in a Nutrient Film Technique (NFT) hydroponic setup using Internet of Things (IoT) technology and the ThingSpeak cloud platform. The developed system consists of an ESP32 microcontroller integrated with pH, Total Dissolved Solids (TDS), and DHT11 sensors for real-time monitoring of water quality and environmental parameters. Sensor data serve as the primary data source and are continuously uploaded to the ThingSpeak cloud for remote visualization and analysis. A rule-based automated control algorithm was implemented to maintain optimal pH and nutrient concentrations. Based on sensor feedback, dosing pumps were activated using pre-defined threshold values and timed dosing cycles to automatically adjust pH and TDS levels. pH sensor calibration was performed using standard buffer solutions and validated through regression analysis against measurements obtained from a digital pH meter. Experimental results demonstrated reliable system performance, with the pH sensor achieving a coefficient of determination ( $R^2$ ) of 0.9862 indicating a strong correlation between sensor readings and reference measurements. The automated dosing mechanism successfully maintained water quality parameters within the desired range, while hydroponically grown plants exhibited faster growth, healthier root development and higher yield compared to conventionally cultivated soil-based plants. The integration of ThingSpeak enabled effective cloud-based monitoring and data logging supporting remote management of the hydroponic system. The findings indicate that the proposed IoT enabled automated hydroponic system is a cost-effective and efficient solution for precision agriculture, particularly in urban and land-constrained environments.

**Keywords:** Hydroponics, IoT, NFT System, ESP32, pH Control, TDS Monitoring, Automated Dosing, ThingSpeak, Smart Agriculture, Precision Farming

## 1. Introduction

Nepal is an agricultural country, yet the progress in the agricultural sector has not been fully satisfactory (Gauchan, 2008). Most farmers still rely on traditional cultivation methods, which often result in lower agricultural productivity and reduced crop yields. The development of agriculture is essential for improving the country's economic and financial condition. However, investment in agricultural research remains very low with less than 0.4% of the agricultural GDP allocated for research activities which is far below the internationally recommended 1%. To address these challenges, hydroponic farming can be considered an effective alternative to conventional soil-based farming.

Hydroponics is a modern farming technique in which plants are grown without soil. Instead of soil, plants receive nutrients through water enriched with minerals and essential elements. Since soil is not directly necessary for plant growth, crops can survive with the help of water, air, nutrients, light, and proper environmental conditions. This method also helps reduce plant diseases that are commonly caused by contaminated soil. One of the major advantages of hydroponics is water conservation, as the system reuses water rather than allowing it to drain away,

saving up to 95% more water compared to traditional irrigation methods. Furthermore, hydroponics enables the production of clean, fresh and healthy vegetables without requiring pesticides, large farming spaces or dependence on seasonal climate conditions.

Traditional farming practices involve excessive use of pesticides and insecticides, which contribute to soil degradation and environmental pollution. In addition, rapid and unmanaged urbanization has reduced agricultural land, limiting farming production. Conventional agriculture also consumes nearly 70% of the world's freshwater resources, creating serious water shortage issues due to runoff and wastage.

The main objective of this study is to design and develop a cost-effective and user-friendly IoT-based automatic hydroponics system. The system is intended to monitor important parameters such as pH level, nutrient supply, temperature, and humidity in real time. The study specifically aims to create an NFT-based hydroponic prototype, integrate an automated control system, and provide remote monitoring access through the internet using IoT technology.

This system can help produce healthy vegetables in less time and within limited space while providing higher yields than conventional farming methods. It is especially useful in urban areas where agricultural land is scarce. Moreover, the study can be expanded into a smart hydroponic greenhouse system that allows crops and vegetables to be cultivated in a fully controlled environment, including off-season farming.

## **2. Literature Review**

The concept of growing plants without soil has a long historical background, beginning with early experiments documented in Francis Bacon's (*Sylvarum*, 1627) published posthumously which laid the foundation for water-based plant cultivation. John Woodward conducted experiments on spearmint using different water sources and observed that plants grew better in impure water compared to distilled water, highlighting the importance of dissolved minerals (Woodward, 1699). By the mid-19th century, scientists had identified essential mineral elements required for plant growth and between 1859 and 1875, Julius von Sachs and Wilhelm Knop advanced solution culture techniques establishing the scientific basis of soilless cultivation (Sachs, 1859-1875). Solution culture which involves growing plants in nutrient solutions without soil became a widely used method in plant physiology research and is considered an early form of hydroponics.

In 1929, William Frederick Gericke of the University of California popularized the idea of using nutrient solutions for large-scale agricultural production and successfully demonstrated tomato cultivation without soil (Frederick, 1929). He later introduced the term "hydroponics" in 1937, which marked a major milestone in modern soilless farming systems. Subsequent research in hydroponics has expanded significantly focusing on system design, efficiency, and automation. Nikesh Gondchawar and R.S. Kawitkar highlighted IOT based smart agriculture systems where sensors and devices are interconnected through wireless communication enabling both manual and automated control modes (Gondchawar & Kawitkar, 2016). Similarly, Mamta D. Sardare and Shraddha V. Admane reviewed hydroponic systems emphasizing their advantages, limitations and operational challenges compared to traditional soil-based farming (Sardare & Admane, 2013).

Further, Madhuri Shrikant Sonawane analyzed hydroponics as an emerging technology addressing issues like land scarcity, declining soil fertility, and water management problems, while also reviewing different cultivation techniques and crop suitability (Sonawane, 2018). In another study, Nisha Sharma and co-authors examined various hydroponic systems such as wick, drip, NFT and deep-water culture, along with optimal pH and EC levels and their applications in water conservation (Sharma, 2018).

More recently (Velazquez-Gonzalez, 2020) emphasized hydroponics as a viable solution for small, medium and large-scale production, integrating modern technologies such as IoT, AI and Big Data for improved efficiency. They also highlighted the importance of sensors, microcontrollers like Arduino and Raspberry Pi, and mobile-based monitoring systems for semi-automated and fully automated setups. Overall, the literature consistently shows that hydroponics has evolved from basic nutrient solution experiments to advanced smart farming systems offering sustainable solutions to challenges in modern agriculture while opening pathways for automation and precision-based cultivation.

### 3. Methodology

#### 3.1 System Architecture

The system design is broken down into two main categories:

- i) **Hardware:** The system connects sensor data to ThingSpeak and users enabling automated monitoring and control of water pH and electrical conductivity while also tracking temperature and humidity. The system consists of ESP32(microcontroller), relay module (electrical switch of mains voltage), pH sensor (electronically chemical fission device that measures the hydrogen-ion activity), DHT11 sensor, nutrients unit (made of mineral salts dissolved into water, NPK is chosen the nutrients) and TDS sensor (measures the electrical conductivity in a solution).
- ii) **Software:** An IoT-based system using ESP32 collects data from pH, TDS and DHT11 sensors and uploads it to the ThingSpeak cloud for storage and monitoring.

Figure 1 illustrates an IoT-based NFT hydroponic system integrated with automated nutrient and pH monitoring and control. The pH sensor and TDS (EC) sensor continuously measure the pH level and nutrient concentration of the circulating nutrient solution in the hydroponic pipes. These sensor readings are sent to an ESP32 microcontroller which processes the data and uploads it to the ThingSpeak cloud platform for real-time monitoring and data logging. Based on the measured values, the ESP32 controls a relay module that operates the submersible pump and dosing pumps. The submersible pump circulates the nutrient solution through the NFT channels while the dosing pumps automatically add nutrient solution or pH-adjusting agents whenever the measured parameters deviate from the desired range.

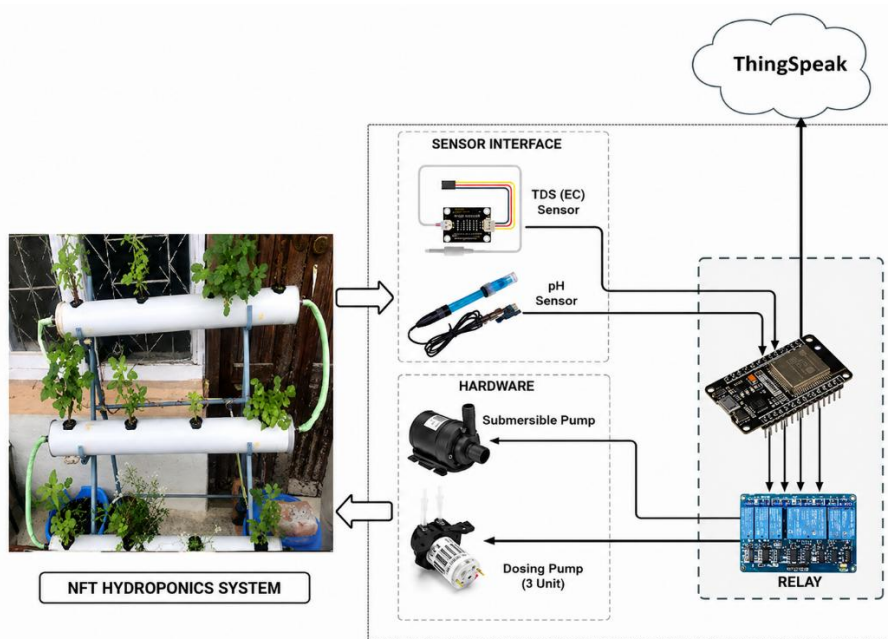


Figure 1. Block Diagram of the System

#### 3.2 Implementation of the system

Design and implementation of automatic hydroponic system is focused on the mechanical structure, water flow and circulation in the system along with the measurement and the control of the required nutrients and pH solution. The implementation has been described in two aspects:

- i) Mechanical Portion
  - a) Metallic stand for supporting the water pipes

For physical implementation, a stable supporting frame was constructed to hold the entire system securely even during water circulation. A strong stand was fabricated using half-inch metal pipes with proper welding, measuring 80 cm in width, and fitted with welded hooks to support horizontal PVC pipes.

b) Piping for water flow

A 10-ft long PVC pipe of 4-inch diameter was equally divided into three sections of 3.33 ft each and arranged horizontally with a slight slope to form the NFT hydroponic channels. Each channel contains four evenly spaced 2-inch holes to hold net cups, allowing the plant roots to remain partially immersed in the nutrient solution while PVC caps and hose connections were sealed properly to prevent leakage. A 30-liter reservoir and a 12V DC submersible pump were used to ensure continuous circulation of water throughout the system.

c) Bucket (Reservoir) size calculation

The water pipe dimension: Height (h) = 10 feet (304.8 cm), Diameter (d) = 4 inches (10.16 cm), Radius (r) = 5.08 cm, Volume of the pipe (cylinder) =  $\Pi r^2 h = 24711 \text{ cm}^3$ . With full water filled condition: Volume of water within the pipe = 24.7 liters. During no flow water condition, two-third of total water volume remains within the pipe =  $\frac{2}{3} * 24.7 = 16.47$  liters. The water tank must contain water greater than the water volume during no-flow conditions, as this is the minimum water level required by the system and therefore required volume of water tank is 20 – 30 litres.

d) Plantation

The hydroponics study consisted of two distinct cultivation phases. First, Amaranthus and coriander seeds sowed on May 24, 2022 sprouted after three days. Seedlings transitioned to NFT channels after 2–3 weeks, growing healthily under manual monitoring. The second cycle focused exclusively on Amaranthus to test system automation capabilities.



Figure 2. Seeding and germination in coco coir

The seeding of amaranth second time was done on 14-Sept, 2022 and it was germinated after three days.



Figure 3. Seeding and germination of amaranth second time

- ii) Automation Portion
  - a) pH sensor

The board's analog output voltage ( $P_o$ ) connects directly to an ESP32 analog input pin. The ESP32 internal ADC converts this incoming signal into a 12-bit digital value. Arduino IDE code then processes this digital data to recalculate the original analog voltage. This conversion relies strictly on the mathematical expression defined in equation (1).

$$\text{Voltage} = \frac{\text{Measure} * 3.3}{4095} \quad \text{(Equation 1)}$$

This analog voltage is then converted into pH value using the expression shown in equation (2).

$$P_H = -2.545 * \text{voltage} + 11.91 \quad \text{(Equation 2)}$$

Three different ways were performed to calibrate and confirm the readings of  $P_H$ .

- Disconnecting the probe and short-circuiting the board's input terminals with a 3.3V supply should yield a 1.65V output, simulating a neutral pH of 7. Initial deviations require calibration using the board's trimmer potentiometer. However, rotating this trimmer in either direction only minimized the voltage to 2.4V (verified via multimeter) instead of the required 1.65V. This inability to adjust the voltage confirms a hardware defect in the circuit board.



Figure 4.  $P^H$  Sensor Board

- To properly calibrate the system, standard buffer solutions of pH 4 and pH 7 were tested. Because the hardware trimmer failed to adjust the neutral pH voltage to the expected 1.65 Volts, a software mapping technique was implemented instead. The actual voltage generated by the pH 7 solution was directly mapped to a value of 7, and the process was repeated for the pH 4 solution. By utilizing these two baseline reference points, a linear calibration equation was derived to calculate the precise pH of any unknown solution. Following the software mapping procedure, verification was required to confirm the code's accuracy for unknown liquids. Consequently, a digital pH meter was introduced as a benchmark reference. After initial calibration of the meter, seven to eight distinct solutions of varying acidity were prepared. Because the precise pH of each solution was pre-established, we successfully compiled the comparative data—consisting of the digital meter readings and the corresponding analog output voltages from the sensor board as detailed in Table 1.

Table 1. pH Calibration

| S.N. | Analog Output voltage from sensor board (v) | pH value confirmed by pH Meter |
|------|---|--------------------------------|
| 1    | 3.08  | 3.8                            |
| 2    | 2.57  | 5.3                            |
| 3    | 2.48  | 5.4                            |
| 4    | 2.68  | 5.0                            |
| 5    | 2.72  | 4.9                            |
| 6    | 2.77  | 4.7                            |

Using not only two mapped values as in previous case, this time various mapped values were used and an equation given in equation (ii) having least error was formed finally. The straight line with minimum error has been obtained and shown in Figure 5. The equation was implemented in the code to find the pH of other solutions.

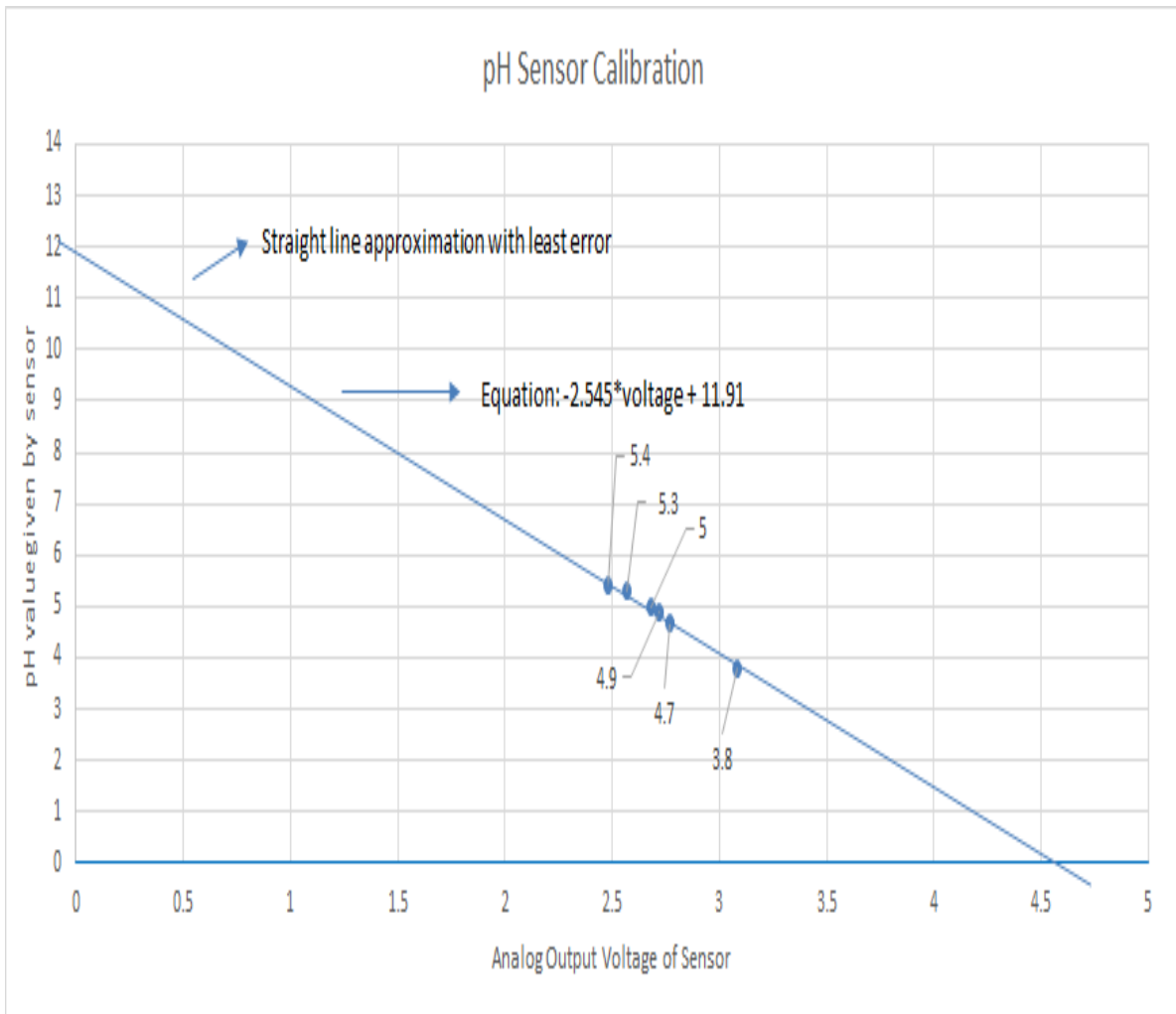


Figure 5.  $\text{pH}$  Sensor Calibration

- To maintain the target hydroponic water pH of 6.0 within the optimal 5.5–6.5 range, an automated dosing system replaces manual adjustments. A pH sensor continuously monitors the reservoir and automated dosing pumps dispense pH Up or Down solutions to counter natural drift. To prevent over-correction due to delayed mixing, the system uses a timed operational loop based on empirical testing: a 1-second pulse of concentrated solution yields a 1 mL displacement and a 0.5 pH shift. For precise control, the solution is diluted 1:20 with water. Consequently, the pump runs for 21 seconds to deliver the equivalent 1 mL dose of active chemical. If the pH deviates from the target by more than 0.5, the pump triggers for one 21-second cycle. The system then enters an experimentally determined 8-minute settlement delay to allow thorough mixing before reassessing the pH and determining if further dosing is required.

b) TDS Sensor

It also has a probe as electrode having two metal terminals to be dipped into the solution, and a circuit board as shown in Figure 6.

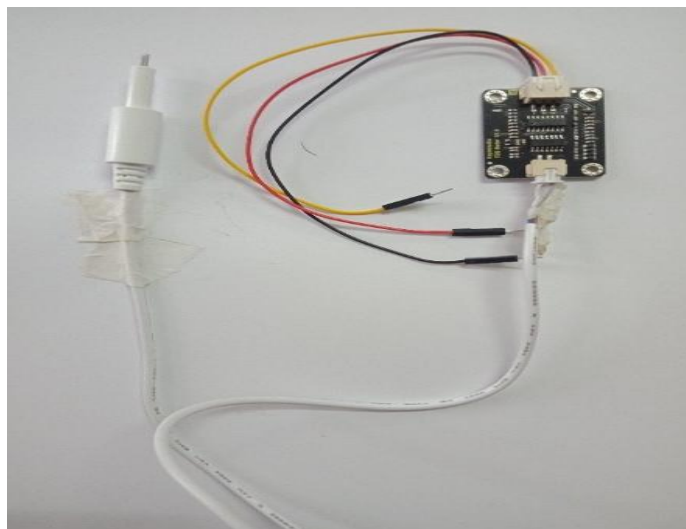


Figure 6. TDS Sensor Module

The sensor board has three pins to be interfaced with microcontroller, V+, V- and analog output. The analog output pin is connected to analog input pin of the ESP32 and is converted into digital value by ADC. This is then converted into equivalent analog voltage using the expression shown in equation (3).

$$Voltage = \frac{digitalValue * 3.3}{4095} \tag{Equation 3}$$

This voltage is then finally converted into TDS value in ppm (parts per million) using this formula shown in equation (4).

$$TDS\ Value = (133.42 * (voltage)^3 - 255.86 * (voltage)^2 + 857.39 * voltage) * 2 \tag{Equation 4}$$

Change of ppm in 1 liter water with NPK solution has been shown in Table 2.

Table 2. Change in ppm with Nutrient Solution Added

| Quantity of NPK added | New TDS value |
|-----------------------|---------------|
| 0 ml                  | 0 ppm         |
| 0.5 ml (tentative)    | 460 ppm       |
| 0.5 ml (tentative)    | 834 ppm       |

Nearly 450 ppm gets changed for 0.5 ml NPK solution added in 1 liter of jar water. Mirroring the pH control mechanism, a dedicated dosing pump manages nutrient delivery to maintain target Total Dissolved Solids (TDS) levels. The Amaranthus plants require an initial target of 500 ppm for the first 2–3 weeks escalating to a range of 900–1000 ppm in later growth stages. The system automates replenishment by triggering a single nutrient dose whenever the measured concentration drops below the baseline by a set threshold. Empirically, running the pump for 40 seconds with concentrated solution elevates the reservoir by 100 ppm. For example, during the early stage, if the TDS falls to 400 ppm, the pump activates for exactly 40 seconds. A subsequent 8-minute stabilization delay prevents over-dosing allowing the mixture to settle before the sensor takes a new reading. If the target threshold is still unmet after this window, consecutive 40-second cycles deploy until the water matches the desired concentration.

c) DHT Sensor

To read the temperature and the humidity of the nearby environment of the hydroponic setup, DHT11 sensor has been used with ESP32. The values will be displayed in Serial Monitor.

d) IoT

The obtained values of pH, TDS, Humidity and the Temperature will be uploaded to the cloud, ThingSpeak. The overall procedure of methodology is summarized in flowchart as shown in Figure 7.

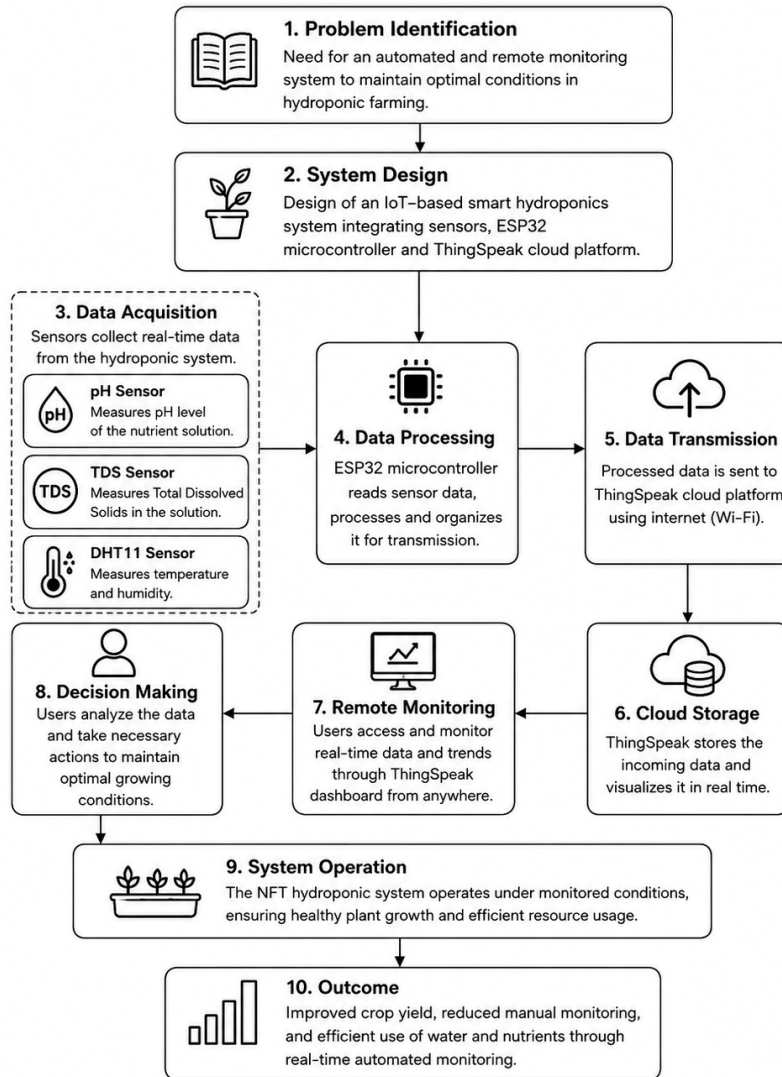


Figure 7. Flowchart of Methodology

## 4. Results and Discussions

### 4.1 Outcome Regarding Mechanical Setup

The stand was stable and strong enough to support the PVC pipes, and no leakage or obstruction in water flow was observed during operation. During power failure, about 2.3 inches of water remained in the PVC channels which was sufficient to keep the plant roots submerged.

### 4.2 Plantation

The plants grown hydroponically for the prototype is shown in Figure 8 The plants seem to be grown healthily.



Figure 8. Hydroponic plant

### 4.3 pH Sensor Data

The pH values measured by the sensor were verified by comparing them with the actual pH values of different solutions obtained using a pH meter. The corresponding analog voltage at the sensor board output pin was also recorded. The verification results are presented in Table 3.

Table 3. pH Sensor Measurement and Verification

| S.N. | Analog Output voltage from sensor board (v) | pH value confirmed by pH Meter | pH value read by pH sensor | Error |
|------|---|--------------------------------|----------------------------|-------|
| 1    | 3.08  | 3.8                            | 4.06                       | 0.26  |
| 2    | 2.57  | 5.3                            | 5.36                       | 0.06  |
| 3    | 2.48  | 5.4                            | 5.54                       | 0.14  |
| 4    | 2.68  | 5.0                            | 5.01                       | 0.01  |
| 5    | 2.72  | 4.9                            | 4.96                       | 0.06  |
| 6    | 2.77  | 4.7                            | 4.82                       | 0.12  |

Furthermore, regression analysis was performed between the pH values confirmed by the pH meter and the pH values measured by the pH sensor. The coefficient of determination ( $R^2$ ) was calculated. The  $R^2$  value of 0.9862 indicates a very strong linear relationship between the sensor readings and the pH meter readings. This means that approximately 98.62% of the variation in the sensor-measured pH values can be explained by the actual pH values measured by the pH meter, confirming the high accuracy and reliability of the pH sensor as indicated in figure 9.

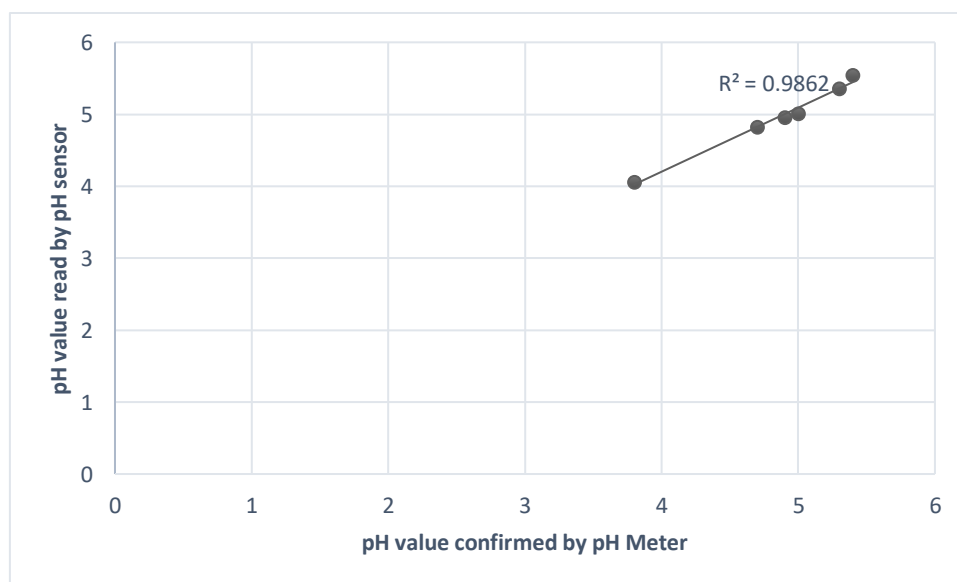


Figure 9. Regression Analysis between P<sup>H</sup> values

### 4.4 TDS Sensor Data

The working of the TDS Sensor has been tested by taking the readings of TDS value of water by adding salt gradually. The data is shown in Table 4. It shows that the sensor module is working properly as it kept on showing increasing TDS value of the water when salt is kept adding into the water.

Table 4. TDS sensor working test

| Solution                | TDS Value in ppm |
|-------------------------|------------------|
| Tap Water               | 144 ppm          |
| With 1 pinch salt added | 196 ppm          |
| With 2 pinch salt added | 210 ppm          |
| With 3 pinch salt added | 230 ppm          |
| With 4 pinch salt added | 274 ppm          |
| With 5 pinch salt added | 292 ppm          |

### 4.5 Final Data Readings

The visual data documenting the system's sensor operations and calibration includes pH readings for standard buffers (pH 4 and 7), the probe water and the reservoir as well as the system's response before and after adding a pH up solution. Additionally, it features corresponding TDS and pH sensor data and DHT11 humidity readings under normal conditions and during steam exposure. The final testing phase involved connecting all three sensors simultaneously to monitor live data through the Arduino IDE serial monitor. This data was uploaded to ThingSpeak, where Figure 10 illustrates the graphical trends and Figure 11 displays the corresponding numeric values.

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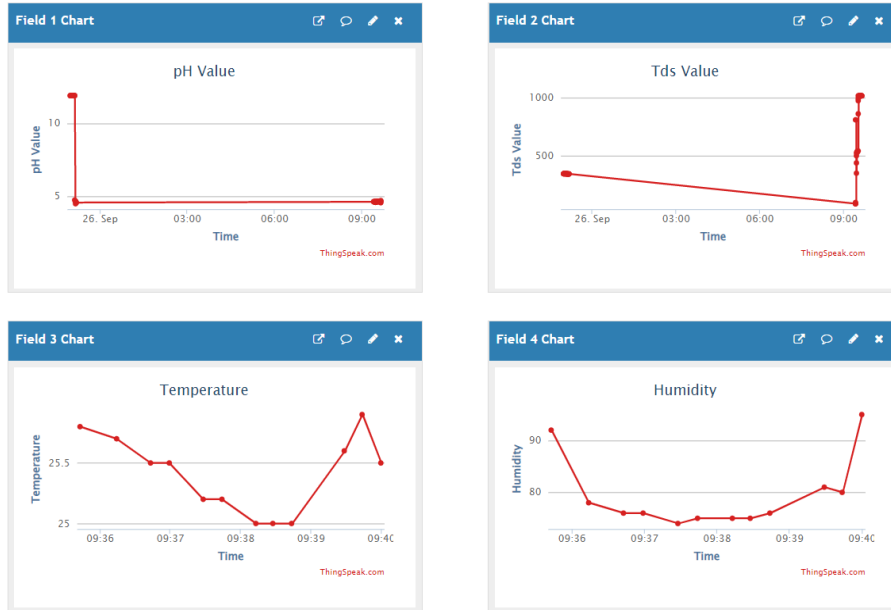


Figure 10. Readings from ThingSpeak graphically

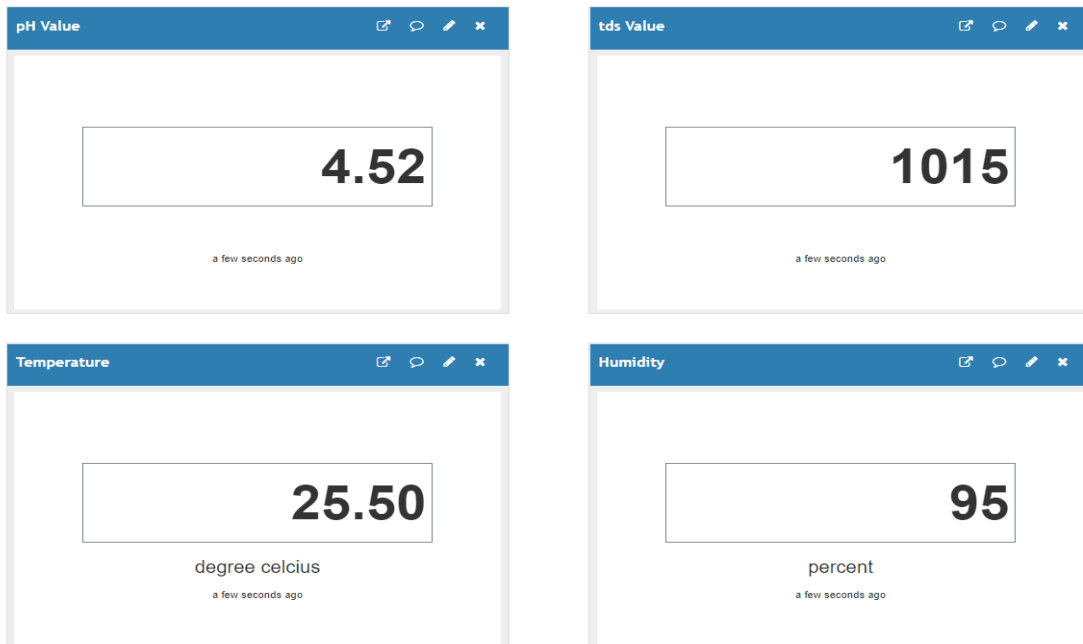


Figure 11. Readings from ThingSpeak in Data (Numeric) Form

#### 4.6 Comparison

To establish a comparative baseline, a control plant was cultivated using traditional soil methods. Figure 12 provides a side-by-side comparison with the hydroponically grown plant on the left and the soil-based plant on the right. The results demonstrate that the hydroponic system produced a significantly higher yield. Furthermore, the hydroponic plants exhibited larger, longer and more robust root structures, alongside accelerated overall growth rates. A major operational advantage observed in the hydroponic system was the complete absence of weed growth, contrasting sharply with the weed management required for soil-based cultivation.



Hydroponic versus Soil based plant (1<sup>st</sup> Phase Plantation)



Hydroponic versus Soil based germination (2<sup>nd</sup> Phase Plantation)

Figure 12. Comparison of hydroponic and soil-based plant

## 5. Conclusion and Recommendations

### 5.1 Conclusion

This study successfully demonstrated the design, implementation and deployment of an automated, Internet of Things (IoT) enabled hydroponic cultivation system. By utilizing a robust structural framework consisting of metallic supports and 4-inch PVC piping, the physical setup proved highly viable for space-constrained urban environments. The core contribution of this work lies in replacing manual agricultural monitoring with an automated sensor-actuator feedback loop. Through the integration of pH and TDS sensors, the system maintained optimal water chemistry profiles by automatically triggering dosing pumps to deliver precise chemical adjustments. Microclimate variables were also successfully tracked using the DHT11 sensor. Furthermore, the incorporation of the ThingSpeak cloud platform fulfilled the IoT monitoring requirement, providing reliable graphical and data-driven data logs accessible remotely.

Experimental comparisons with traditional soil-based cultivation revealed that the automated hydroponic system yielded substantial agronomic advantages:

- a. **Accelerated Growth & High Yield:** Hydroponic crops grew faster, achieved larger physical dimensions and developed significantly larger, longer and stronger root systems.
- b. **Resource Efficiency:** The closed-loop fluid design drastically minimized water and fertilizer waste.

- c. **Maintenance & Spatial Optimization:** The system completely eliminated weed growth, lowering maintenance overhead while maximizing vertical and horizontal space efficiency in high-density, crowded urban settings.

### **5.2 Recommendations for Future Work**

As a future enhancement, the temperature and the humidity can also be controlled for better growth. Moreover, the data written into the cloud can be read and fed to any web site or mobile application for easy monitoring of the sensors' data.

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