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Smart Hydroponic Systems: Optimizing Nutrient Levels with IoT Connectivity

Abstract: - Maintaining precise nutrient levels is essential for the thriving success of hydroponic systems. This comprehensive study delves into the intricate interplay of climatic conditions and nutrients, meticulously analysing various parameters like Total Dissolved Solids (TDS), pH, and electrical conductivity (EC) within a sophisticated smart hydroponic vertical Nutrient Film Technique (NFT) setup designed for leafy greens. The innovative system integrates a wireless sensor network and Internet of Things (IoT) connectivity, employing ESP32 microcontrollers as the primary unit alongside complementary hardware components for continuous and real-time monitoring of critical nutrient parameters. The investigation delves into the dynamic relationship between environmental factors and the growth patterns of spinach plants. Through a thorough examination of the extensive dataset gathered via deployed sensors, the study unveils variations in environmental parameters throughout various stages of plant development, including germination and root establishment. The study aims to elucidate the significance of each parameter in optimizing plant growth in hydroponic environments by analysing data associations. Results show higher Total Dissolved Solids (TDS) values correlate with better plant growth, while reduced pH levels harm plants. These findings are crucial for interpreting disease symptoms, aiding farmers in identifying issues early and optimizing yields. Understanding how nutrient values affect plant health enables proactive problem-solving. This research provides valuable insights into smart hydroponic systems, informing precision agriculture decisions.

Keywords: Internet of Things, Hydroponic Systems, Nutrient Management, Smart Agriculture, Environmental Monitoring, Automated Farming

I. INTRODUCTION

In modern agriculture, hydroponic farming—which uses water as a growing medium for crops instead of traditional soil—has grown in popularity. This novel method involves suspending plant roots in water and using fertilizers to add extra nutrients that are necessary for healthy growth. Notwithstanding its benefits, hydroponic farming depends heavily on environmental conditions, therefore close observation is required. Variations in humidity and temperature can affect the nutrient solution's pH levels, which can have an impact on the health of the plants. Recent research has emphasized the crucial role pH plays on yield, especially in the field of hydroponic spinach cultivation. A crucial factor in nutrient availability and absorption, pH, a measure of acidity or alkalinity, has a direct impact on plant health and overall output. A ground-breaking study found that lowering the pH of the nutrition solution to 4.0 significantly inhibited the growth of spinach. Because critical nutrient concentrations were at their lowest at this low pH, plant growth was hindered, perhaps as a result of hydronium ion damage. Interestingly, at pH values of 4.5, 5.0, and 5.5, spinach showed consistent growth of both shoots and roots. At pH values of 4.5 and 5.0, any loss in shoot growth seems to be from less nutrient uptake than from a direct pH influence. These results demonstrate the complex link between pH values and the success of hydroponic spinach production.

a. Hydroponic Leafy Greens

After going through various studies and reviews, some *Leafy Greens* that are beneficial on small/ medium scale and on large commercial scale also, are

1. Cilantro (Dhania): One can start a hydroponics system with a cilantro .It needs a lesser budget.

2. Lettuce: Hydroponic systems are ideal for growing lettuce and other leafy greens. It's important to select the proper variety of lettuce, which includes Butterhead lettuce, romaine, little gem and more.

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3. Spinach: In hydroponics, spinach grows incredibly well, much like lettuce. If we continue to harvest it, it grows quickly and becomes abundant. This is well-liked and healthful because of its antioxidant qualities. We can observe the spinach growing in 7–21 days.

4. Basil: Hydroponics can be used to cultivate a wide variety of basil types, including lemon, sweet, Thai, Italian, and purple basil.

Table 1 presents the required nutrients value for some plants.

Table 1 Essential parameters for Leafy Greens

Sr	**Vegetable**	**pH**	**EC**	**TDS**
1	Spinach	6.0-7.0	1.8-2.3	1260-1610
2	Lettuce	5.5-6.5	0.8-1.2	560-840
3	Cilantro	5.8-6.4	1.2-1.8	800-1000
4	Basil	5.5-6.0	1.0-1.6	700-1120

While selecting the plants, following factors are considered:

1. Space availability in urban settlement. 2. Local climate
3. Expert reviews 4. IoT set up to be installed in particular space

Spinach is one of the few crops that can be grown successfully during summer and winter. Generally, spinach growers prefer a closed hydroponic system to grow their spinach using coco peat as a growing medium. These systems have a 1m wide bed with a divider in between resulting in two channels of approximately 0.5m each. The planting density varies between 8 and 16 plants/m^2, while baby spinach can reach densities of up to 100 plants/m^2. The factors that decide the planting density are

1. The type and variety of spinach (baby spinach, chard, Swiss chard etc.)
2. Local climate
3. Pesticide equipment used

As per agronomists/ experts, it can be said that the ideal planting densities for spinach and Swiss chard are respectively 10 and 12 and 14 plants/m2. Baby spinach will differ based on the kind of development medium that is utilised.

Ideal temperature to grow spinach is between 10^0 C and 28^0 C. The proposed work focuses on spinach plants due to favourable climate conditions.The study involves continuous evaluation of temperature, pH, and TDS.

II. LITERATURE REVIEW

Numerous studies and comprehensive reviews in the literature focus on the design and implementation of hydroponic systems. Authors in [1] and [3] propose IoT-based hydroponic systems that utilize wireless sensor networks to monitor various parameters. In [2], an automated system for detecting tomato plant diseases is proposed, using image processing and feature extraction. Researchers in [4] suggest a framework for resource optimization in smart farming, incorporating data storage, image processing, etc. Addressing the crucial role of irrigation and water supply in farming, [5] presents a robust smart irrigation system. Data analysis plays a significant role in farming, enabling the storage and analysis of data from sensors, as described in [6]. Detecting the freshness of the final produce is discussed in [7], where images of fresh and withered vegetables are captured. In [8], machine learning techniques are utilized for automatic dosing, with monitoring of electrical conductivity (EC) and pH values before determining the nutrition dosage. Scholars in [9] present an automatic hydroponic drip irrigation system that utilizes big data and combines it with IoT/Raspberry Pi technology, providing a solution for drip irrigation management. In [10], a cloud and edge computing approach is proposed to control the concentration of nutrient solution in hydroponic systems. Authors in [11] propose water saving control system based on WSN using ZigBee protocol. [12] Proposes an energy efficient design for smart agriculture with cloud-edge-fog layer structure. For home grown indoor plants, [13] and [14-15] presents the IoT hydroponic set up with LED lights and vertical test beds. With a distinct approach of involving micro fluids, authors in [16] come up with a system using microfluidic based soil nutrition detection unit for measuring pH, EC and nitrate contents in soil using Arduino Atmega. To make it easier, [17] presents a set up that can be connected to mobile app for smart farming. For some plants, EBB and Flow can also be implemented that is focused in the study shown in [18]. Automation is the next step in smart hydroponics and authors in [19] have presented their study for indoor plant growth. Deep Neural Network is used for predictive control using Node MCU, Raspberry Pi and Arduino for humidity and water level [20]. In [21-22], enhanced IoT and hydroponic approach is discussed with current trends and future challenges. Researchers have conducted reviews and surveys in the field of hydroponic farming, focusing on the utilization of modern technologies such as IoT, machine learning (ML), cloud computing, edge computing, and fog computing [23-26]. Communication protocols for hydroponics are discussed in various reviews, including [23-24], [29]. Microcontrollers and sensors play a crucial role in hydroponics and are considered in the literature, as showcased in [25-28]. Large greenhouses are increasingly adopting hydroponic farming methods, as highlighted in [30] The integration of artificial intelligence, machine learning, and IoT has helped the agricultural sector with predictions, accurate parameter measurements, and improved yields, as demonstrated in surveys [31]. K. Gulati et al. [32], S. L. Bangare et al. [33, 36], J. Surve et al. [34], S. Athawale et al. [35] have done good research in the domain of the Internet of Things.

III. SYSTEM ARCHITECTURE

The setup is arranged as shown in Fig 1. It includes pH sensor probe and TDS sensor submersible into nutrition solution, WiFi compatible modules for these two sensors and EPP32 as a main microcontroller.

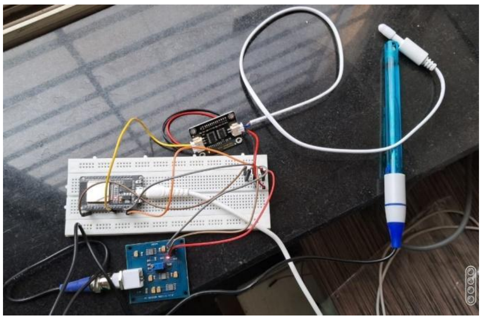

Fig 1 Proposed Circuit for pH and TDS sensing

Using sensors, IoT (Internet of Things) and machine learning into the architecture of a hydroponic system is a cutting-edge approach to precision agriculture, as illustrated in fig 2. This state-of-the-art system will maximize resource utilization, enhance crop yields, and ensure sustainable farming practices. The architecture essentially uses a network of sensors to collect data in real-time on the environmental factors of the hydroponic system, such as pH, temperature, humidity, and nutrient levels. The first stage of hydroponics is data acquisition, where the emphasis is on using Internet of Things (IoT)-enabled sensors for on-going data collection, which sets them apart from conventional digital sensors. A cloud server is essential for storing the sensor data and making it available to farmers at all times. In the future, this feature is quite helpful in comprehending past events like pest attacks and changes in plant conditions caused by weather fluctuations. pH and TDS modules are connected to ESP32. pH sensor electrode and TDS electrode sense the respective values from hydroponic set up that is shown in fig 3.

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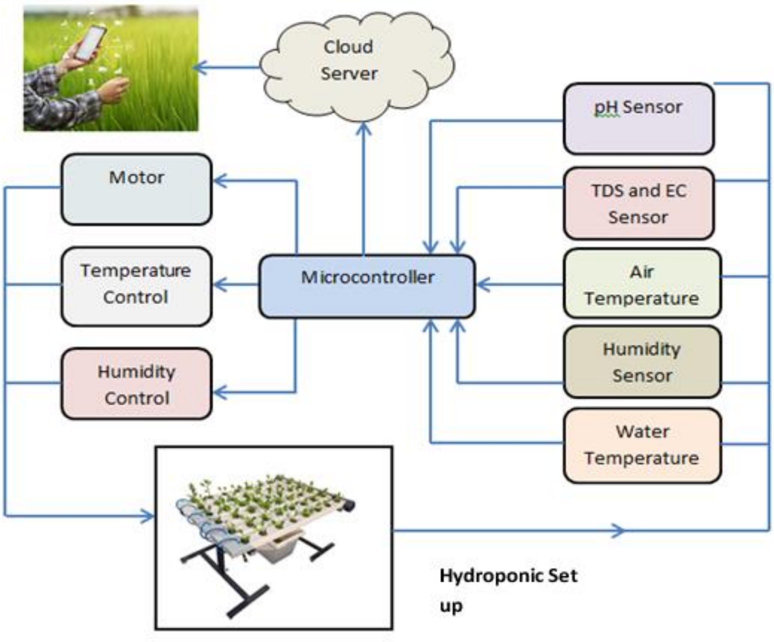

Fig 2 IoT System Architecture for Hydroponic Set Up

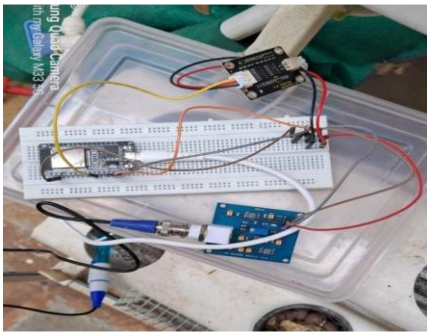

Fig 3 Sensor Network in the hydroponic set up

IV. SENSORS AND MICROCONTROLLER

The careful selection of appropriate sensors is necessary to provide accurate measurements in hydroponic installations. Differential sensors, combination sensors, laboratory sensors, and process sensors are some of the pH sensors that are available. Nonetheless, the pH-sensitive electrode is the sensor that works best in hydroponics. It is advised to use an integrated IoT-enabled module for Total Dissolved Solids (TDS) and Electrical Conductivity (EC) measurements, as this will enable a smooth integration with microcontrollers. The procedure for gathering data is simplified by this module. To help choose the best temperature sensor for the hydroponic system, Table 4 provides a comparison of various temperature sensors. This thorough analysis guarantees that the selected sensor best fits the unique needs of the system

Table 2 Temperature Sensors for hydroponics

Sensor	DHT11	DHT22(AM2302)	LM35	DS18B20
Measures	Temperature Humidity	Temperature Humidity	Temperature	Temperature
Communication protocol	One-wire	One-wire	Analog	One-wire
Supply voltage	3 to 5.5V DC	3 to 6V DC	4 to 30 V DC	3 to 5.5V DC
Temperature range	0 to 50ºC	-40 to 80ºC	-55 to 150ºC	-55 to 125ºC
Accuracy	+/- 2ºC (at 0 to 50ºC)	+/- 0.5ºC (at -40 to 80ºC)	+/-0.5ºC (at 25ºC)	+/-0.5ºC (at -10 to 85ºC)

V. MATERIALS AND METHODOLOGY

The pH sensor is used to measure pH levels at different times of the day so that variations in reaction to changes in the surroundings may be identified. One important metric that measures the amount of dissolved nutrients in water is total dissolved solids (TDS). TDS measurements are carried out at 25 degrees Celsius, which is the ideal growing temperature for plants. The DHT22 sensor is used in the study to measure air temperature and humidity levels simultaneously. Since nutrients dissolve in water, the water temperature is measured using the DS18B20 temperature sensor, which guarantees a complete assessment of the hydroponic environment. All sensors are connected to ESP32 and data acquisition is done for further analysis. Due to WiFi connectivity, some of the values can be tracked using smart phone also as shown in fig 4 and fig 5.

Fig 4 Connectivity on Smart Phone using Server

Fig 5 Temperature and Humidity- Sample Values

Before proceeding further, let's have a look about the nutrient requirements for greens as this work proposes set up for greens, especially Spinach. Growers should be aware about the proportion of all the nutrients. There are two types of nutrients:

1. Macronutrients: Nitrogen, Phosphorus, Potassium
2. Micronutrients: Magnesium, Calcium, Sulphur, Manganese, Iron. Zinc, Copper, Molybdenum, Boron

The environmental parameters that are to be considered for plant growth are:

1. pH value   2. TDS value (ppm)
3. Environmental Temperature   4. Light

In this case study, the effects of change in pH, temperature and TDS value are observed. The study is presented as follows:

A. Case I: Effects of change in pH, keeping TDS constant (800-900)

a) pH value in required range (5.5 to 6.5)

For spinach, the required pH range is 6.0 to 7.0; however, in the germination and initial growing stages, it can be a bit lesser. Following table 5 shows the range of pH for different temperatures.

Table 3 pH values

Temp	pH
25.1	5.8
24.8	5.6
24.9	5.6
25.2	5.8
23.2	5
25.1	5.8
25	5.9
25.5	6.2
25	6

Fig 6 Plant Growth pH 5.5 to 6.5

The plant growth can be observed in fig 6. The plot for the pH values is as shown in fig 7

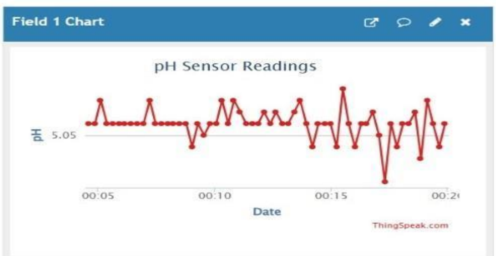

Fig 7 pH sensor readings

b) Reduced pH for sample plants in experimental set up

If the pH value is reduced up to 2 to 3, the plant growth is affected and some brown spots at the tip and edge of the plant are observed.

b.1) A plant was observed for the low pH in the initial stage. The pH was dropped around 2.8 to 3 just after germination and the growth was observed. This is shown in fig 8 (a and b)

Fig 8 (a) sample plant with affected growth

Fig 8 (b) Spotted and dried leaf tip

b.2) pH value of the plant is dropped after it started growing well. The plant grew up to 4-5 inches and then the pH was dropped and changes were observed. The leaf tip and edge was observed with drying and spots as shown in fig 9 (a and b)

Fig 9 (a) expected growth before low pH

Fig 9 (b) dried leaves and spotted leaves after lowering pH

The change in pH values is shown in following fig 10.

Fig 10 pH values for intermediate change

B. Case II Change in TDS keeping pH constant (approximately 6)

TDS is the measure of total dissolved solids in the nutrient solution. For spinach, according to agronomists, 1260-1600 ppm (parts per million) TDS is required. In the proposed experimental set up, two scenarios were tested. First with the less TDS in the range of 800-900 ppm and the 1000-1100 ppm. It was observed that plant growth was fastened with the increased TDS values. This can be observed from the following fig 11. The TDS values are also given in the same.

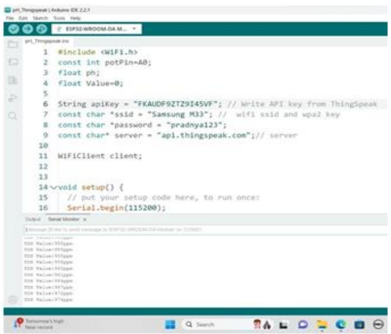

Fig 11 (a) plant height at 970ppm Fig 11 (b) Serial monitor: TDS approximately 975 ppm

As the TDS value was increased, the plant growth was better as shown in fig 12.

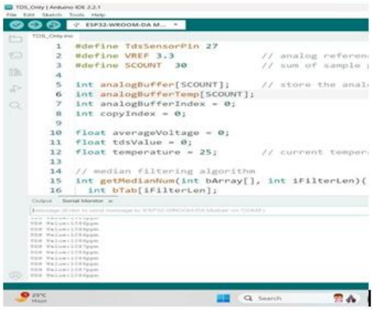

Fig 12 (a) plant growth at 1090ppm   Fig 12(b) Serial monitor: TDS approximately 1100ppm

With all the parameters within required range- pH= 6, TDS = 1100-1200 ppm and environmental temperature = 25^0 C, the plant growth and the root growth is shown in fig 13 (a and b) . It was observed that the plant appearance was fresh green rather than other plant appearances with changes parameters.

Fig 13(a) Maximum height at pH=6, TDS=1100ppm   Fig 13 (b) root growth at pH=6, TDS= 1100ppm

C. Case III : Effect of environmental temperature on pH value

It was observed that in winter season, the pH values dropped in the evening time due to temperature drop. However, there was no significant effect on the plant growth. The changes in values are presented in following table 4.

Table 4 Change in pH values with change in environmental temperature

Temp	pH
23.2	4.9
23	4.8
23.2	5
24	5
23.2	5
22	4.6
23.3	4.7
23.8	4.8

VI. CONCLUSION

The analysis indicates that temperature and humidity fluctuations affect plant growth, impacting parameters such as pH and TDS. Spinach quality, measured by plant height, fresh green colour, and robust roots, thrives at a pH of 5.5 to 6.5. Optimal TDS levels range from 1000-1200 ppm, surpassing 800-900 ppm for vibrant colour and expected height. In hydroponics, where plants grow in water-nutrient solutions, the presence of long, hairy roots in pipes signals high-quality growth. This proposed urban hydroponic system serves as an initial stage setup, offering valuable insights for cultivating quality produce in controlled environments.

Author Contributions

Work Conceptualization by Pradnya Kulkarni and Vinaya Gohokar; material and methodology by Pradnya Kulkarni; software design by Pradnya Kulkarni, Kunal Kulkarni; validation is done by Pradnya Kulkarni, Vinaya

Gohokar, and Kunal Kulkarni; formal analysis was conducted by Pradnya Kulkarni; investigation in case study was conducted by Pradnya Kulkarni; resources, Pradnya Kulkarni; original draft was prepared by Pradnya Kulkarni; writing—review and editing, Pradnya Kulkarni; visualization, Pradnya Kulkarni, Kunal Kulkarni; supervision, and project administration was done by Vinaya Gohokar; funding acquisition – not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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