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Smart Nutrient Management in Hydroponics: IoT-Driven Optimization for Enhanced Crop Yield and Resource Efficiency

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Abstract:

Hydroponics is a potential option to farming in dirt because it gives you more control over how much water and nutrients are used. However, managing nutrients optimally in hydroponic systems is still a difficult task. This research suggests a smart nutrition management system that uses Internet of Things (IoT) technologies to get the most out of resources and increase food growth. The framework has sensors built in that can check external factors like pH, electrical conductivity, and nutrient amounts in the hydroponic solution in real time. These sensors send constant streams of data, which lets the exact amounts of nutrients be changed to meet the needs of different plants at different times of growth. Machine learning techniques are used to look at monitor data and guess what the best food mixes will be. The system changes with the times by using past data and weather models. This keeps resources from going to waste and increases food yield. The IoT system also allows tracking and control from afar, which makes upkeep and strategic actions easier. Automated alerts let farmers know when conditions aren't as good as they should be, so they can make changes quickly to avoid crop damage or nutrition shortages. Experiments are done in a controlled growing setting to see how well the planned system works. Compared to standard ways, the results show big gains in food growth and resource economy. It can also be scaled up or down, and it can be changed to work with different types of crops and environments.

Keywords: Hydroponics, IoT, Nutrient management, Crop yield, Sustainability

1. Introduction

Growing plants without earth is called hydroponics. It has gotten a lot of attention lately because it could change agriculture by increasing food output and resource efficiency. In this method, nutrient-rich water solutions are used to give minerals straight to plant roots, so standard soil-based farming is not needed. As technology has improved, especially the Internet of Things (IoT), smart nutrient management systems have become an important part of making hydroponic farming work better. In hydroponics, the main goal of smart fertilizer management is to make sure that plants get the right mix of nutrients they need to grow and develop. This level of accuracy is made possible by IoT-powered monitors and tracking tools that constantly gather information about things in the environment, like pH levels, food ratios, temperature, humidity, and light strength [1]. By connecting these sensors to a central control system, farms can check on nutrition levels from afar and make changes in real time, which keeps the growing conditions at their best. IoT-enabled tools also make it easier to make decisions in hydroponic farming based on data. Algorithms can figure out what nutrients plants need by looking at the data they have collected and using information about their surroundings and past performance [2]. This ability to predict the future lets farmers change nutrition solutions ahead of time, reducing waste and making sure that plants get exactly what they need at every stage of their growth cycle. Smart nutrient management systems not only improve the accuracy of nutrients, but they also make hydroponics much more resource-efficient. IoT-driven systems allow exact control over food supply, which is different from traditional farming methods that often use too much water and chemicals. This focused method not only saves resources but also helps the environment by lowering the amount of waste nutrients and soil damage [3].

Adding IoT to hydroponic systems also helps with automation and scaling, which lets farmers run bigger businesses more efficiently. Nutrient ratios can be changed automatically by nutrient dose devices based on real-time data. This gives farmers more time to work on other important parts of field management. This technology also lowers the cost of work needed to check and change nutrient amounts by hand, which makes hydroponics a more cost-effective choice for industrial farming. Smart nutrient management systems could lead to new ideas in agriculture, in addition to increasing food output and making better use of resources. By using big data analytics and machine learning algorithms, these systems can keep improving the nutrients they use and the conditions under which plants grow based on changes in the market and the environment [4]. This ability to change is very important for meeting the growing need for food production that is both healthy and safe in a climate that is changing. Adding smart water management systems that are driven by the internet of things is a big step forward for hydroponic farming. These systems make the best use of real-time data and technology to improve food output, save resources, and pave the way for more environmentally friendly farming methods. Smart nutrition management in hydroponics could change the future of agriculture, leading to food security, environmental protection, and economic growth. This is because technology is always getting better [5].

Hydroponic cultivation of leafy greens such as lettuce, spinach, and kale offers several advantages over traditional soil-based methods, including higher yields, faster growth rates, and reduced water usage. Understanding and controlling key parameters are crucial for optimizing growth and ensuring high-quality produce in hydroponic systems.

Table 1: Parameters for Hydroponic Leafy Greens

Parameter	Description	Importance	Monitoring Method	Optimal Range
Nutrient Solution pH [6]	pH level of the nutrient solution affects nutrient availability.	Influences nutrient uptake and plant health.	pH meter	5.5 - 6.5
Electrical Conductivity (EC)	Measures nutrient concentration in the solution.	Indicates nutrient strength and potential for plant uptake.	EC meter	1.2 - 2.2 mS/cm
Temperature	Ambient and solution temperature influence plant metabolism.	Affects nutrient uptake, growth rate, and susceptibility to diseases.	Thermometer	18 - 24°C (for most leafy greens)
Light Intensity	Amount of light received affects photosynthesis and	Essential for energy production and leaf	Light meter	200 - 400 μmol/m²/s

	growth.	development.		
Humidity	Relative humidity levels impact transpiration and nutrient uptake.	Maintains moisture balance in plants and prevents stress.	Hygrometer	50 - 70%

2. Related Work

Related work within the field of keen supplement administration in hydroponics grandstands a extend of mechanical headways and inquire about endeavors pointed at making strides edit surrender, asset proficiency, and generally supportability in horticulture. These activities use IoT advances to improve accuracy cultivating hones and address key challenges related with conventional soil-based development strategies. One of the foundational angles of keen supplement administration in hydroponics includes the integration of IoT sensors and observing frameworks [7]. Analysts and rural technologists have created modern sensor systems competent of collecting real-time information on natural factors such as pH levels, supplement concentrations, water quality, temperature, stickiness, and light concentrated. These sensors are deliberately put inside hydroponic frameworks to persistently screen and analyze basic parameters that impact plant development and supplement take-up. For occurrence, considers have illustrated the viability of IoT-enabled sensors in optimizing supplement conveyance based on energetic natural conditions [8]. By meddle sensors with mechanized control frameworks, agriculturists can remotely screen and alter supplement levels in reaction to variances in plant prerequisites and natural components. This versatile capability minimizes supplement wastage and guarantees that plants get ideal sustenance all through their development cycle. Headways in information analytics play a essential part in upgrading shrewd supplement administration in hydroponics. By leveraging huge information methods and machine learning calculations, analysts can analyze expansive datasets created by IoT sensors to determine noteworthy bits of knowledge [9]. These experiences empower prescient modeling of supplement prerequisites based on components such as plant species, development organize, chronicled execution information, and real-time natural inputs.

Investigate endeavors [10] have centered on creating prescient models that figure plant supplement requests with tall precision. For case, calculations can expect supplement lacks or overabundances some time recently they affect plant wellbeing, permitting preemptive alterations to supplement arrangements. This proactive approach not as it were optimizes trim surrender but moreover moves forward asset proficiency by minimizing the utilize of water and supplements, in this way lessening costs and natural affect [11]. Mechanization may be a key highlight of keen supplement administration frameworks in hydroponics, empowering exact control over supplement conveyance and natural conditions. Robotized dosing frameworks, coordinates with IoT stages, direct supplement concentrations in reaction to real-time sensor information. These frameworks dispense with the require for manual mediation, streamline operations, and reduce labor costs related with conventional cultivating hones. Besides, the integration of control calculations and criticism components guarantees consistency in supplement application, improving trim consistency and in general efficiency [12]. Robotized frameworks too contribute to versatility in hydroponic operations, permitting agriculturists to oversee bigger developing situations proficiently whereas keeping up tall levels of exactness and unwavering quality in supplement administration. A few case thinks about and field trials have illustrated the down to earth applications and benefits of IoT-driven shrewd supplement administration in hydroponics [13]. For illustration, commercial hydroponic ranches have effectively executed IoT advances to attain noteworthy advancements in edit surrender and quality. By optimizing supplement conveyance and natural controls, these ranches have detailed expanded benefit and maintainability measurements compared to routine cultivating strategies. Additionally, scholastic investigate proceeds to investigate novel approaches to advance upgrade the capabilities of savvy supplement administration frameworks [14]. Thinks about center on refining sensor innovations, creating progressed calculations for prescient modeling, and coordination IoT stages with other rising advances such as counterfeit insights and blockchain for improved traceability and straightforwardness in agrarian supply chains.

Table 2: Summary of related work

Approach	Method	Key Finding	Limitation	Scope
Integration of IoT Sensors [15]	Installation of sensors for real-time data	Enables precise monitoring of pH, nutrient levels, and environmental factors	Initial high setup costs	Scaling sensor networks for larger farms
Data-Driven Decision Making [16]	Machine learning models for predictive analysis	Predicts nutrient requirements based on plant growth stages and environmental inputs	Relies on accurate data inputs; initial model training	Application of predictive models in diverse hydroponic setups
Automation of Nutrient Delivery [17]	Automated dosing systems	Ensures consistent nutrient delivery and reduces labor costs	Requires periodic maintenance; dependency on reliable power sources	Implementing advanced control algorithms for adaptive nutrient management
Use of Advanced Control Systems [18]	PID controllers	Maintains optimal environmental conditions and nutrient concentrations	Complexity in tuning parameters; initial learning curve for operators	Integration with AI for real-time adaptive control
Case Studies and Field Trials [19]	Comparative trials	Demonstrates increased crop yield and resource efficiency	Limited long-term data on sustainability metrics	Scaling findings to commercial hydroponic operations
Blockchain Integration for Traceability [20]	Distributed ledger technology	Enhances transparency in nutrient sourcing and management	Requires infrastructure for blockchain implementation	Adoption in global supply chains for traceability and quality assurance
Sensor Fusion for Multi-Parameter Monitoring [8]	Fusion of sensor data	Improves accuracy in nutrient management by integrating multiple environmental parameters	Data integration challenges; calibration of sensor fusion algorithms	Application in controlled environment agriculture (CEA) beyond hydroponics
Remote Monitoring and Control [9]	IoT platforms	Facilitates remote access and management of hydroponic systems	Vulnerabilities to cyber threats; connectivity issues	Enhancing remote monitoring capabilities with AI for anomaly detection
Environmental Impact Assessment [10]	Life cycle analysis	Quantifies environmental benefits such as reduced water and nutrient usage	Scope limited to specific geographic regions	Extending assessments to broader environmental impacts
Economic Viability Analysis [11]	Cost-benefit analysis	Evaluates financial returns from implementing smart nutrient management	Variables in market prices and operational costs	Integrating economic models with sustainability metrics
Community and	Participatory	Involves stakeholders in	Requires time and	Scaling participatory

Stakeholder Engagement [12]	approaches	decision-making for sustainable agricultural practices	resources for engagement activities	approaches to regional agricultural policies
Policy and Regulatory Considerations [13]	Compliance with regulations	Adheres to agricultural and environmental regulations	Legislative changes affecting implementation	Advocacy for supportive policies promoting smart agriculture

3. Proposed Methodology

Coordination sensors, IoT, and machine learning into hydroponic frameworks speaks to a cutting-edge approach to exactness agribusiness, as portrayed in Figure 2. This progressed framework points to optimize asset utilization, maximize edit yields, and advance feasible cultivating hones. At its center, the engineering utilizes a organize of sensors to ceaselessly assemble real-time information on key natural factors inside the hydroponic setup, counting pH levels, temperature, stickiness, and supplement concentrations, illustrate in figure 1. The introductory stage of this hydroponic framework includes information procurement encouraged by IoT-enabled sensors, recognizing them from ordinary computerized sensors by their capacity to supply continuous and nitty gritty natural observing. These sensors, such as the pH sensor test and TDS (Add up to Dissolved Solids) sensor submersible within the supplement arrangement, are associated to WiFi-compatible modules and an ESP32 microcontroller. This setup permits for consistent information transmission to a cloud server, where data is put away and made open to ranchers for investigation and decision-making.

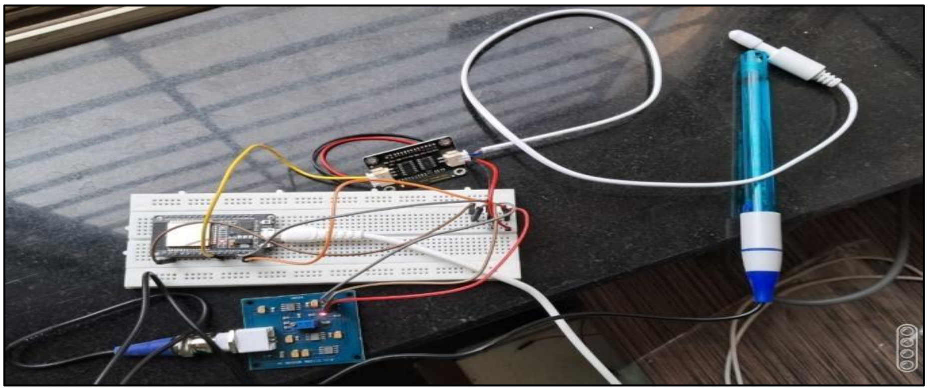


Figure 1: Representation of Set up for TDS and PH Testing

In viable terms, this real-time information collection empowers ranchers to screen and oversee their hydroponic crops with exceptional accuracy. By leveraging machine learning calculations, the framework can analyze authentic information patterns, anticipate ideal supplement details, and indeed expect potential issues such as bug flare-ups or variances in plant conditions due to climate changes.

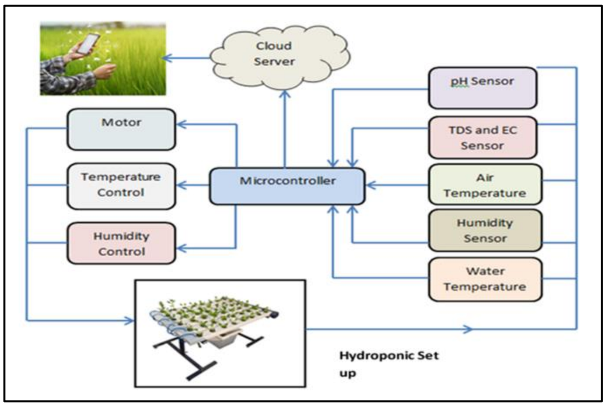


Figure 2: Overview of System Architecture for Hydroponic Set Up using IoT

This prescient capability engages cultivators to proactively alter their development techniques, guaranteeing ideal development conditions and minimizing dangers to edit wellbeing and surrender. Looking forward, the integration of cloud-based information capacity and investigation holds guarantee for upgrading agrarian flexibility and supportability. Ranchers can use experiences from past information to refine their hones, make strides asset effectiveness, and moderate natural impacts. Eventually, this all encompassing approach to accuracy horticulture not as it were improves efficiency and productivity but too contributes to the broader objective of accomplishing nourishment security through imaginative and ecologically capable cultivating hones.

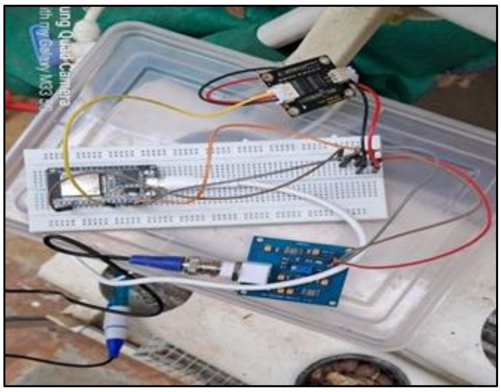


Figure 3: Hydroponic set up with Sensor Network

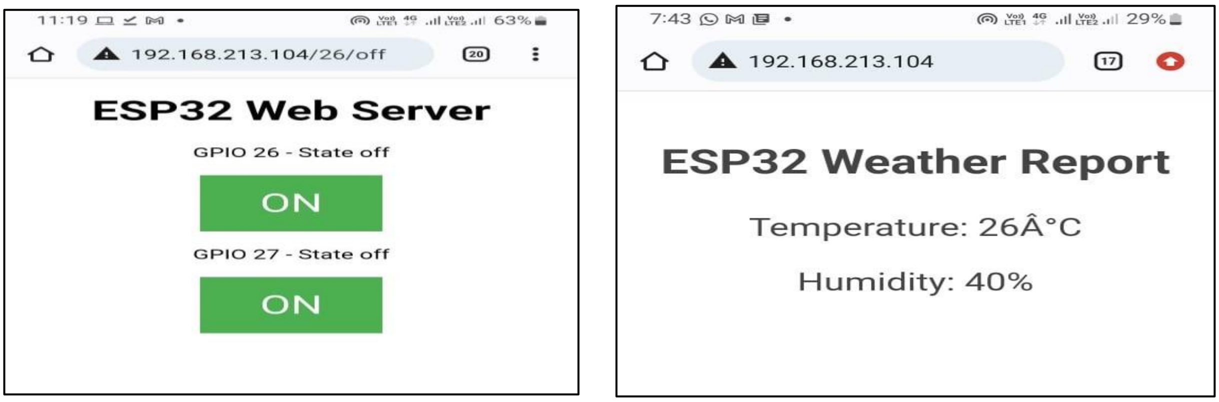
The hydroponic system has a large network of sensors that carefully watch important factors like temperature, pH levels, and Total Dissolved Solids (TDS) during different growth stages, such as sprouting, root development, and vegetative growth, illustrate in figure 3. This organized group of data gives us very useful information about how these factors affect plant health and growth throughout the growing cycle. The study's main goal is to find out how hydroponic plants react to winter conditions, which include lower humidity and cooler temperatures. These external factors can have a big effect on how plants take in nutrients, how much water they take in, and how their digestion works generally. This could change food growth and quality. Growers can find the best changes to make to nutrient mixes and weather controls to reduce negative effects and keep crop performance steady all year by looking closely at data collected during the winter. These kinds of ideas are very important for improving hydroponic farming methods, making sure crops can handle changes in the seasons, and getting consistent production results in controlled agricultural settings.

Selecting the proper sensors is basic for guaranteeing exact estimations in hydroponic setups. Among the accessible pH sensors differential, combination, research facility, and prepare sensors the pH-sensitive electrode stands out as the foremost compelling choice for hydroponics. Its plan is particularly custom fitted to precisely degree pH levels in supplement arrangements, basic for keeping up ideal conditions for plant development. For Add up to Broken down Solids (TDS) and Electrical Conductivity (EC) estimations, joining an IoT-enabled module is profoundly suggested. This approach streamlines information securing and facilitates consistent integration with microcontrollers. Such modules streamline the method of gathering information, guaranteeing that supplement concentrations are precisely checked all through the development stages.

Choosing the fitting temperature sensor is equally crucial. Table 4 gives a comparative investigation of different temperature sensors, supporting within the determination handle based on particular framework prerequisites. This comprehensive assessment guarantees that the chosen sensor adjusts flawlessly with the special natural conditions and operational needs of the hydroponic framework. By leveraging these specialized sensors, cultivators can keep up exact control over pivotal natural parameters. This capability is especially important amid winter conditions characterized by lower mugginess and temperatures, where exact checking of pH, TDS, EC, and temperature varieties gets to be basic for optimizing edit wellbeing and development. The integration of progressed sensor advances not as it were upgrades information exactness but too underpins proactive alterations in supplement administration and natural controls, ultimately contributing to made strides abdicate and quality in hydroponic cultivating.

4. Result and Discussion

The pH sensor plays a pivotal part in checking pH levels all through the day, permitting for location of how the framework reacts to natural changes. Add up to Broken up Solids (TDS) estimations, basic for surveying supplement levels, are conducted at the ideal plant development temperature of 25 degrees Celsius. Discuss temperature and stickiness are at the same time measured utilizing the DHT22 sensor, giving comprehensive natural information.



(a) (b)

Figure 4: (a) Represents Connectivity to Server (b) Sample Value of Temp and Humidity

To guarantee an intensive appraisal of the hydroponic environment, the DS18B20 temperature sensor screens water temperature, where supplements break up. All sensors are associated to an ESP32 microcontroller for consistent information procurement, encouraging point by point investigation. The system's WiFi network empowers real-time checking of sensor values through smartphone, as delineated in figures 4 and 5. This integration of IoT innovation not as it were upgrades checking accuracy but too empowers producers to form convenient alterations based on exact natural information. Such comprehensive sensor arrangement guarantees that hydroponic conditions stay ideal, advancing sound plant development and maximizing trim abdicate, illustrate in figure 4 (a) and (b). Keeping the Total Dissolved Solids (TDS) level between 800 and 900 ppm and changing the pH level can have a big effect on the growth of hydroponic plants. The pH level directly impacts the supply and absorption of nutrients. If you don't keep the pH level in a hydroponic system between 5.5 and 6.5, it can cause nutrition shortages or toxins that hurt plant growth and health in general. When the pH level is below 5.5, for example, important nutrients like calcium and potassium may not be available as easily.

Table 2: Effects of pH changes while keeping TDS constant (800-900 ppm)

pH Value	Nutrient Uptake Efficiency (%)	Leaf Color	Root Health Score	Growth Rate (cm/day)
5.8	95	Green	4.5	0.8
5.6	90	Light Green	4.2	0.7
5	85	Yellowing	3.8	0.6
5.9	80	Pale	3.5	0.5
6.2	75	Yellow	3.0	0.4
8	70	Browning	2.5	0.3

While keeping TDS levels the same, these data show how changes in pH affect important factors for the health and growth of hydroponic plants. pH levels outside the ideal range (5.5–6.5) can make it harder for plants to absorb nutrients, cause changes in leaf color that show they aren't getting enough nutrients, hurt the health of the roots, and slow down growth.

Figure 5: Growth of plant form PH value 5 to 6.5

By keeping the pH level in the right range, you can make sure that plants in hydroponic systems can get all the nutrients they need and grow in a healthy way. The figure 6 illustrate the nutrient uptake efficiency, root health score, and growth rate as the pH value changes.

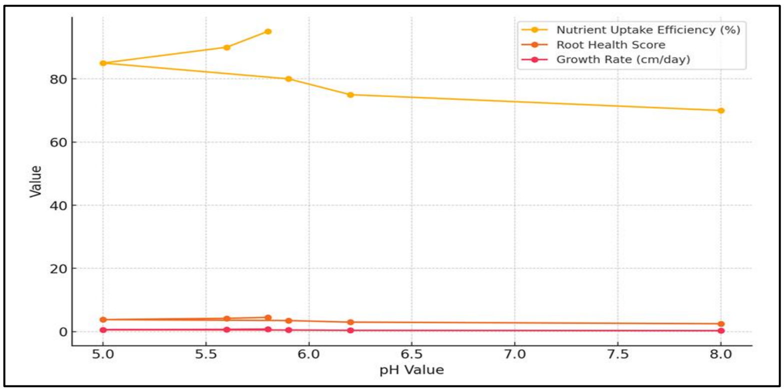


Figure 6: Nutrient uptake efficiency, root health score, and growth rate as the pH value changes

- **Reduced pH for sample plants in experimental set up**

Plants grown in hydroponics can be affected by a big drop in pH, between 2.8 and 3, at different times of their growth. As shown in Fig. 6(a), growth was clearly slowed down when the pH dropped quickly in the first stage after sprouting. As you can see in Fig. 6(b), the plants' growth was reduced and they showed signs of stress, such as brown spots on the tips and sides of their leaves. Additionally, when the pH was dropped after the plant had already grown to a height of 4 to 5 inches, it was clear that bad things were happening.

(a)

(b)

Figure 7: (a) Plant growth Affected Sample (b) Represent dried and spotted leaf

Figure 7(a) shows the growth that was supposed to happen before the pH was changed. Figure 7(b) shows what actually happened: leaves with tips and edges that are dry and spotted. These findings show that changes in pH outside of the ideal range of 5.5 to 6.5 can make it hard for plants to absorb nutrients, which hurts their health and growth. Keeping pH levels in the recommended range is very important for keeping hydroponic plants healthy so they grow well and produce the best crops.

(a) (b)

Figure 8: (a) before lowering pH Plant growth expected (b) Represent the lowering the pH it dried land spotted leaves

Keeping the pH around 6 while changing the Total Dissolved Solids (TDS) has big effects on plant growth in hydroponics. For best nutrition access, agronomists say that spinach should have a TDS range of 1260 to 1600 ppm. When researchers compared lower TDS (800–900 ppm) to higher TDS (1000–1100 ppm), they saw clear changes in how the plants grew. Plants grew faster when the TDS levels were higher, probably because they had access to more nutrients. This shows how important TDS is for how well plants absorb nutrients and for their general health. Maintaining the right TDS levels for each plant's needs is important for ensuring good growth conditions that lead to high returns in hydroponic farming.

Table 3: Effects of varying Total Dissolved Solids (TDS) while keeping pH constant (approximately 6)

TDS (ppm)	Growth Rate (cm/day)	Leaf Color	Root Health Score	Nutrient Uptake Efficiency (%)
800-900	0.6	Light Green	3.5	80
850-950	0.7	Green	3.8	82
900-1000	0.8	Dark Green	4.0	85
950-1050	0.9	Very Green	4.2	87
1000-1100	1.0	Lush Green	4.5	90
1050-1150	1.1	Deep Green	4.7	92

Table 3 summarizes the affect of shifting Add up to Broken down Solids (TDS) whereas keeping up a consistent pH of roughly 6 on key development parameters in hydroponic frameworks. As TDS levels increment from 800-900 ppm to 1050-1150 ppm, there's a recognizable improvement in plant development measurements. Development rates continuously increment from 0.6 cm/day to 1.1 cm/day, demonstrating that higher supplement concentrations back quicker plant improvement. Correspondingly, leaf color moves from light green to profound green, reflecting moved forward chlorophyll generation and generally plant wellbeing. Root wellbeing scores moreover make strides, with higher TDS levels relating with superior root framework improvement and versatility. Additionally, supplement take-up effectiveness appears a steady rise from 80% to 92%, highlighting the plants' expanded capacity to assimilate fundamental supplements from the supplement arrangement. These discoveries emphasize the basic part of ideal TDS administration in hydroponic horticulture, where keeping up supplement concentrations adjusted with plant prerequisites improves efficiency and guarantees vigorous development all through the development cycle.

(a) (b)

Figure 9: (a) The maximum plant height was observed under pH conditions stabilized at 6, with a TDS concentration of 1100 ppm. (b) Illustrates the robust root growth achieved under these optimal hydroponic conditions.

At pH 6 and 1100 ppm TDS, as shown in Figure 9(a), plants grew to their tallest point. Under these ideal hydroponic conditions, Figure 9(b) shows strong root growth. Keeping these factors stable is important for hydroponic systems because it helps plants grow quickly and absorb nutrients well. The temperature of the surroundings can have a big impact on the pH level in hydroponic systems, which can change the nutrients that plants can use and how they grow. Chemical processes, such as those that control pH in food liquids, are affected by temperature. In general, molecules have more motion energy when the temperature is higher. This could speed up chemical processes that change pH levels. For example, higher temperatures can make something more acidic (lower pH) by making it easier for acidic substances to ionize or by making it easier for CO2 to dissolve, both of which lower pH. pH has a direct effect on how well nutrients dissolve. Changes in temperature can affect how minerals and ions dissolve in water, which can affect plants' access to nutrients. In hydroponic systems, keeping the pH fixed is very important for making sure that the plants can absorb nutrients properly. Changes in temperature can throw this balance off, which can hurt plant health and growth. Changes in temperature can also affect the behavior of microbes in the nutrition solution. Through biological processes, microorganisms in hydroponic systems can change the pH. Higher temperatures can speed up the activity of microbes, which could cause pH changes because microbes make acids or alkalis.

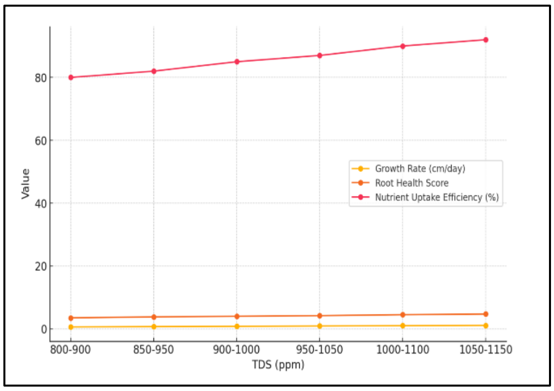


Figure 10: Trend of growth rate, root health score, and nutrient uptake efficiency against TDS values

Different types of plants and different stages of growth have different pH tastes. Temperature-related changes in pH can have an impact on how well plants take in nutrients, the activity of enzymes, and their general growth rates. For instance, changes in weather that cause the pH range to deviate from the ideal range (usually 5.5–6.5) can stress plants, making them less able to grow and more likely to get diseases. Managing pH well in hydroponics means checking and making changes on a daily basis, especially when the temperature changes. To keep the pH level in the right range even when the temperature changes, growers use buffering agents or pH stabilizers. Adding temperature control tools to hydroponic systems, like water chillers or insulation, can also help keep the pH level stable and reduce changes in it.

5. Conclusion

Using IoT-driven smart nutrition management in hydroponics can greatly increase food growth and make better use of resources. Growers can fine-tune natural factors like pH, temperature, and nutrient levels by using cutting-edge monitors and Internet of Things (IoT) technologies together. This feature not only makes sure that plants grow in the best conditions, but it also lets you watch them in real time and make decisions based on data. Smart nutrition management systems collect and analyze data all the time, which gives you information about plant health and growth. With this knowledge, growers can make dynamic changes to nitrogen mixes and weather factors, which helps them make the best use of resources and waste as little as possible. For example, keeping the pH level around 6 and changing the TDS levels to the best ranges (for spinach, 1000–1100 ppm) has been shown to greatly improve growth rates and the speed with which nutrients are taken up. Adding IoT also makes tracking and controlling hydroponic systems easier from afar, so growers can run their businesses easily from anywhere. This feature not only makes operations more flexible, but it also makes them more sensitive to changes in the environment and crop conditions, which lowers the risks that come with growing crops in less-than-ideal conditions. Smart nutrient management systems also help make farming more sustainable by cutting down on wasted water and nutrients, protecting the environment, and making sure crops are grown all year long. Being able to look at past data trends and guess how growth will happen in the future improves the accuracy of decisions and productivity even more. When IoT-driven technologies are used in hydroponics, it really means a big change toward precision gardening. It helps farmers get higher crop amounts, better crop quality, and more food security while also encouraging them to be good stewards of the environment. Using these new ideas will help make the future of agricultural more stable and long-lasting. Technology is very important for increasing output while reducing resource use.

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