International Journal of Informatics and Communication Technology (IJ-ICT)
Vol. 15, No. 2, June 2026, pp. 900~908
ISSN: 2252-8776, DOI: 10.11591/ijict.v15i2.pp900-908

IoT-enabled smart hydroponic system using nutrient film technique for precision agriculture

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Article Info

Article history:

Received Feb 28, 2025
Revised Dec 19, 2025
Accepted Mar 30, 2026

Keywords:

Hydroponics
Internet of things
Nutrient film technique
Sensor-based automation
Smart farming

ABSTRACT

The study aims to develop an internet of things (IoT)-enabled automated hydroponic system using the nutrient film technique (NFT) to optimize plant growth with minimal human intervention. The system integrates sensors, microcontrollers, and cloud-based monitoring to maintain optimal conditions for crops. The system utilizes Arduino Uno, ESP8266 Wi-Fi module, and sensors including pH, TDS, DHT11 and water level sensors. Data collected from these sensors is processed in real time, allowing automated adjustments through relay-controlled water and nutrient pumps. The system transmits data to the ThingSpeak IoT platform, enabling remote monitoring and predictive analytics. The proposed hydroponic system ensures stable environmental conditions, improving plant growth efficiency. Key parameters such as pH, TDS levels and humidity are maintained within optimal ranges. The automated system reduces manual intervention, enhances water and nutrient efficiency, and increases yield consistency compared to traditional farming methods. The IoT-based NFT hydroponic system demonstrates significant potential in urban agriculture and controlled environment farming. By leveraging automation, AI-driven analytics, and cloud-based monitoring, it provides a scalable and sustainable solution for precision farming. Future advancements may include AI-based predictive analytics, solar-powered energy solutions, and robotic automation for further optimization.

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1. INTRODUCTION

Hydroponics is a soilless plant cultivation method that delivers essential nutrients directly to plant roots through a nutrient-rich water solution. This approach optimizes plant growth by ensuring controlled nutrient delivery, reducing water consumption, and eliminating soil-related constraints such as pests and diseases. Over the years, hydroponics has gained prominence in urban agriculture, where space and soil quality are limited. Among various hydroponic techniques, the nutrient film technique (NFT) is one of the most efficient. It involves continuously circulating a thin film of nutrient-rich water over plant roots within a shallow channel, allowing optimal nutrient absorption while ensuring proper aeration [1]-[5]. The Smart NFT Hydroponics System enhances this method by integrating internet of things (IoT) technologies, automation, and real-time monitoring to improve efficiency and scalability.

This study proposes an IoT-enabled automated NFT hydroponic system that utilizes Arduino Uno, ESP8266 Wi-Fi module, and multiple sensors (pH, TDS, temperature, humidity, and water level sensors) to maintain ideal growth conditions [6]-[9]. The system collects real-time environmental data, which is processed and transmitted to the ThingSpeak IoT platform for remote monitoring and predictive analytics. Automated relay-controlled water and nutrient pumps adjust parameters dynamically, reducing human intervention while ensuring consistent plant health and yield [10]-[14].

The implementation of this smart hydroponic system offers several advantages, including:

– Efficient water and nutrient usage – Recirculating system reduces resource wastage.
– Automated monitoring and control – Real-time adjustments enhance accuracy.
– Faster growth and higher yield – Optimal conditions accelerate plant development.
– Space optimization – Ideal for urban vertical farming where land is scarce.
– Scalability and sustainability – Suitable for small-scale home gardens to large commercial farms.

This research explores the design, development, and evaluation of the IoT-based NFT hydroponic system, highlighting its potential in precision agriculture and sustainable farming [15]-[21]. The following sections discuss the system architecture, methodology, experimentation, and results, demonstrating the effectiveness of IoT-driven automation in modern hydroponics [22]-[25].

2. RESEARCH METHOD

The fundamental block diagram of the proposed automatic vertical hydroponic system is shown in Figure 1. It consists of six major components: the power meter, vertical hydroponic structure, primary power source, control system and sensors, an online database, and a Wi-Fi module. This configuration allows monitoring via an IoT platform from any smart device connected to the system. A key component is the power meter module, which continuously monitors energy consumption across system elements like pumps and lighting. This ensures efficient power usage and supports system expansion by identifying optimization opportunities. The hydroponic system is controlled by an Arduino Uno, which serves as the central microcontroller. It is connected to an ESP8266 Wi-Fi module that transmits sensor data to the ThingSpeak platform. Several sensors-pH, TDS, DHT11 (for temperature and humidity), and water level-are integrated to monitor environmental and nutrient conditions. Based on sensor input, the relay module activates the water pump as needed.

Collected sensor data is processed by the Arduino, which dynamically adjusts water and nutrient flow to maintain optimal plant growth. This data is uploaded in real time to ThingSpeak, facilitating remote monitoring and historical trend analysis. To support full automation, the system independently manages pH, temperature, electrical conductivity (EC), and water levels. Electromechanical relays control devices such as dosing pumps and artificial lights. All data is wirelessly transmitted to ThingSpeak via the ESP8266 module.

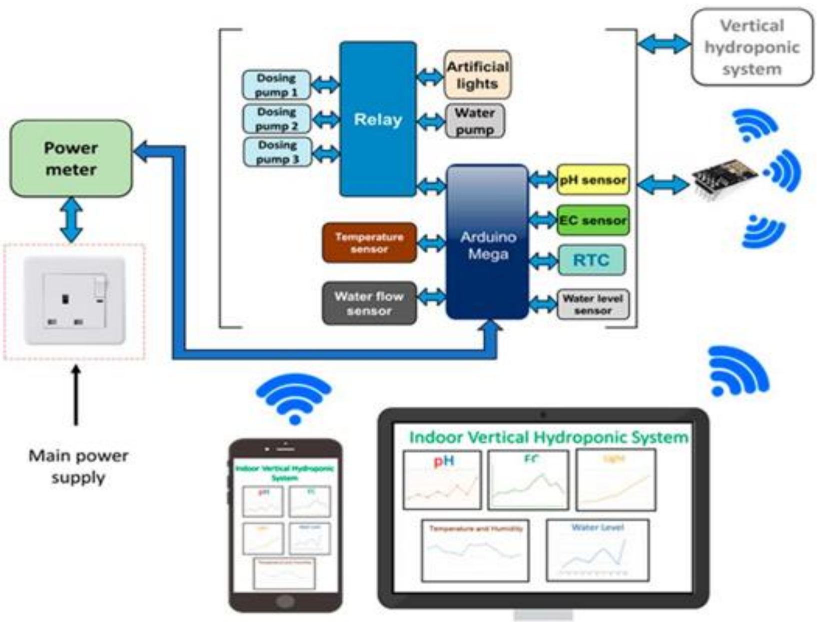

Figure 1. Block diagram of the proposed hydroponics system

2.1. Power meter module
This module ensures the system runs efficiently by monitoring energy usage of all active components. It helps identify potential energy savings and provides statistics for overall system optimization, supporting the project's sustainability goals.

2.2. Vertical hydroponic structure
Designed for vertical farming, this structure optimizes space-ideal for urban environments. Plants are placed in channels where a thin layer of nutrient-rich solution circulates, providing moisture and nutrients directly to the roots while gravity assists in recycling the excess solution.

2.3. Primary power source
A reliable power source-either from the grid or solar panels-supplies energy to the entire system. If solar energy is used, battery backups are included to ensure uninterrupted performance, enhancing system reliability and sustainability.

2.4. Control system and sensors
The control system, built around the Arduino microcontroller, receives data from various sensors:
- pH sensor: measures solution acidity or alkalinity, crucial for nutrient absorption.
- TDS sensor: monitors nutrient concentration to ensure balanced plant nutrition.
- DHT11 sensor: tracks ambient temperature and humidity to support healthy plant growth.
- Water level sensor: ensures consistent reservoir levels to prevent pump failure.

The Arduino processes this sensor data to control pumps and dosing units, maintaining an ideal environment.

2.5. Online database and remote monitoring
Using the ThingSpeak IoT platform, all sensor data is uploaded in real time via Wi-Fi. This allows users to remotely view system status, track performance, and access historical data for analysis. It also supports predictive maintenance and remote troubleshooting.

2.6. NFT architecture
NFT enables continuous delivery of a nutrient film to plant roots within shallow gullies. This setup improves oxygenation, minimizes water usage, and is highly efficient for fast-growing crops like leafy greens and herbs. Figure 2 illustrates the NFT layout, which supports scalable and eco-friendly farming. As shown in Figure 2, the NFT system mimics the natural movement of water in streams, allowing nutrients to be evenly distributed while maintaining the right level of moisture. The thin film of solution ensures that roots remain aerated, preventing issues like root rot, which can occur in overly saturated environments. One of the key advantages of NFT is its ability to maximize resource efficiency. Since the nutrient solution is recirculated rather than drained, this method significantly reduces water and fertilizer consumption compared to traditional farming or even some other hydroponic systems. This makes it an eco-friendly option for sustainable agriculture. NFT is particularly well-suited for fast-growing crops such as leafy greens like spinach and medicinal herbs like Tulsi. These plants thrive in the controlled conditions provided by NFT, leading to rapid growth and higher yields. Additionally, the lightweight and modular nature of NFT setups make them easy to scale and adapt for different growing environments, from small-scale urban farms to larger commercial operations. By optimizing water, nutrients, and oxygen delivery, NFT enhances plant health and productivity while minimizing waste, making it a highly effective technique for modern hydroponic farming.

2.7. Water flow and dosing control
Water pumps and sensors regulate nutrient flow through the system. If water, pH, or nutrient levels deviate from set thresholds, the system automatically adjusts by activating relevant pumps or adding corrective agents via dosing systems.

2.8. IoT integration
The integration of IoT enables real-time automation and monitoring. Parameters such as light intensity, temperature, humidity, and pH are continuously adjusted without manual input. The system ensures consistent performance and improves agricultural accessibility for users with limited experience.

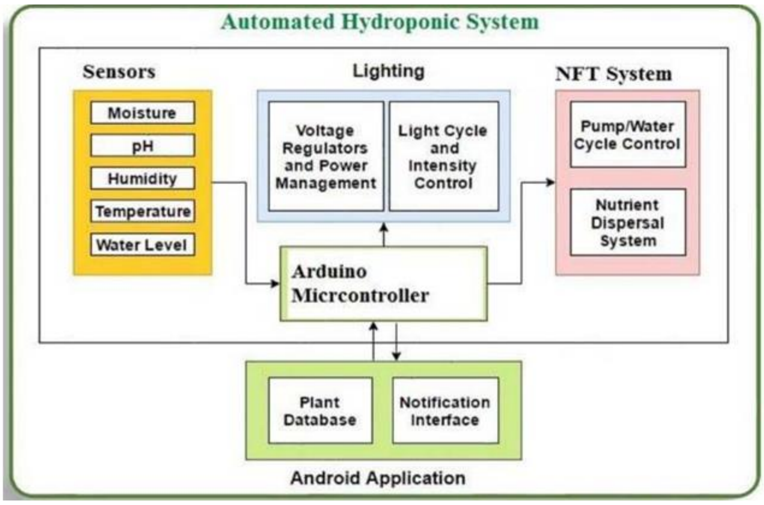

Figure 2. NFT method

3. EXPERIMENTATION

In the proposed method, all sensor readings, such as pH, water level, TDS, temperature, and humidity sensors, together with the power consumption of the system, were broadcast to a web server using the ESP8266 Wi-Fi module. The microcontroller and Wi-Fi module are linked, and it is at the microcontroller that all sensor data is collected and transmitted to ThingSpeak, an open-source IoT platform. ThingSpeak is an excellent choice for an indoor vertical hydroponic system since it is open source, enables MATLAB-based data visualization, and allows for the application of algorithms on the gathered data. This framework simplifies the development of traditional, IoT, and AI approaches, which will be the focus of this endeavour in the future. Additionally, ThingSpeak has eight separate fields that allow for the real-time display of eight different system characteristics without charging a membership fee. The free edition of ThingSpeak also refreshes the channel every 20 seconds, which is sufficient for our application. Additionally, it’s easy to check the system settings, set up several Android-compatible apps to enable the mobile application’s channel without requiring a sign-in on the web browser each time. As a result, a system built on ThingSpeak is a sensible substitute for creating a lucrative system with reliable IoT platform functionalities. It also allows the historical data to be exported in the CSV format for future research, which is very helpful for potential machine learning-based studies.

In Figure 3, the IoT-based NFT hydroponic system is an innovative agricultural approach that optimizes plant growth through automation and real-time monitoring. As depicted in Figure 3. The system integrates an Arduino microcontroller to process sensor data, manage water and nutrient flow, and transmit real-time information to an online database while displaying key parameters on an LCD panel. The Arduino serves as the system’s central processing unit, performing essential computations such as converting light dependent resistor (LDR) values to Lux, controlling water pumps, and monitoring environmental conditions like temperature, humidity, pH, and total dissolved solids (TDS). The system operates autonomously, continuously adjusting conditions to maintain an ideal plant-growing environment. A key feature is automated water level monitoring, ensuring a continuous nutrient film in the gullies to prevent drying or excessive flooding. If pH levels fluctuate due to water addition, the system automatically corrects them by adding the appropriate nutrients. Additionally, it tracks variations in light intensity, humidity, and temperature, issuing alerts when values exceed predefined thresholds.

To enable remote monitoring and efficient farm management, the system employs a Wi-Fi module that follows the IEEE 802.11 standard, transmitting real-time data to a local router and an online database. This connectivity allows users to access critical environmental data from any location, ensuring efficient oversight of the hydroponic system. The system incorporates multiple sensors, including water level, pH, temperature, humidity, and LDR sensors, providing a comprehensive dataset for real-time decision-making. The algorithm continuously analyzes sensor data and executes necessary adjustments, such as activating or deactivating motor drivers to regulate nutrient flow. Timely and precise motor control is crucial in NFT hydroponics to maintain uninterrupted circulation of the nutrient solution, preventing adverse effects on plant health.

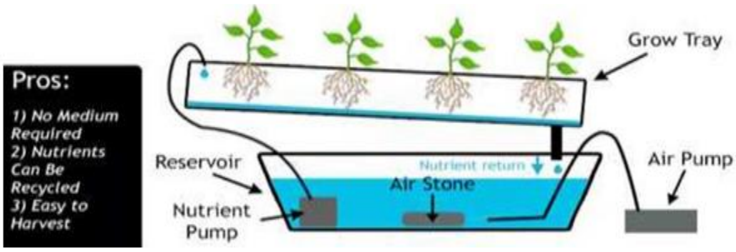

Figure 3. IoT based NFT system

4. RESULTS

For optimal plant growth, a hydroponic system must maintain stable environmental and nutrient conditions. The proposed system shown in Figure 4 achieves this by integrating various sensors and automation components that ensure continuous monitoring and adjustment of key parameters. In the hydroponic system, plants require a stable environment for optimal growth, with specific nutrient and environmental parameters. The system uses a TDS sensor to monitor the concentration of nutrients in the water, making necessary adjustments to maintain the correct balance. Similarly, the pH sensor ensures the water remains within the ideal pH range for nutrient absorption. The DHT11 sensor tracks environmental temperature and humidity, providing data that ensures conditions are favourable for spinach growth. A water level sensor helps prevent pump failure by ensuring there is always enough water for the plants. With the integration of ThingSpeak, the system continuously monitors and adjusts these parameters to maintain optimal growth conditions. If any values fall outside the desired range, the system automatically triggers adjustments, ensuring spinach grows robustly and healthily without manual intervention.

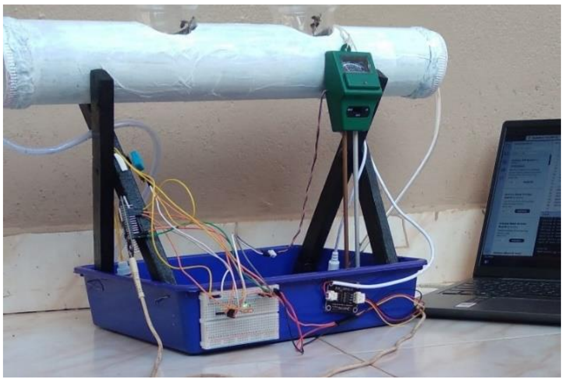

Figure 4. Model of the NFT based smart hydroponics system

ThingSpeak is an IoT platform that aids your smart hydroponics system by efficiently storing sensor data, creating real-time graphs for monitoring, and triggering actions through alerts. It allows you to send sensor data to your ThingSpeak channels using API keys, where the data is securely stored. With ThingSpeak's visualization tools, you can create customizable graphs and dashboards to monitor parameters like temperature, humidity, and pH levels. Additionally, ThingSpeak supports setting up alerts via SMS or email for specific conditions, such as abnormal pH levels. By using ThingHTTP, ThingSpeak can interact with third-party services to send notifications, ensuring timely responses to any critical changes in your hydroponics system. Figures 5 to 8 show variations in key parameters of the hydroponic system.

Figure 5 (Variations of TDS value) – This graph displays the changes in TDS levels, indicating fluctuations in nutrient concentration over time and ensuring plants receive optimal nutrients. Figure 6 (Variations in Temperature) – This figure tracks temperature variations within the hydroponic system, helping maintain an optimal environment for plant growth and preventing heat stress. Figure 7 (Variations in pH value) – This chart illustrates pH fluctuations, which are crucial for maintaining nutrient availability and ensuring proper absorption by plant roots. Figure 8 (Variations in Humidity) – This graph represents changes in humidity levels, influencing plant transpiration and overall growth conditions in the hydroponic system. These figures collectively help monitor and optimize environmental conditions for enhanced plant productivity.

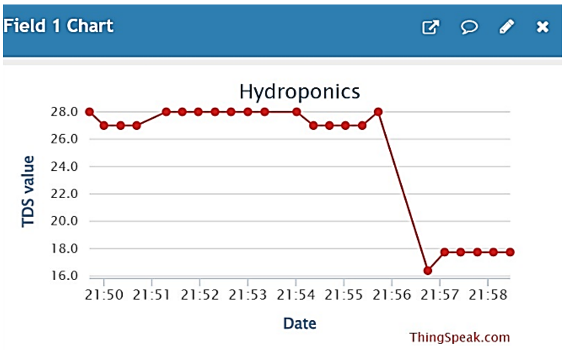

Figure 5. Variations of TDS value

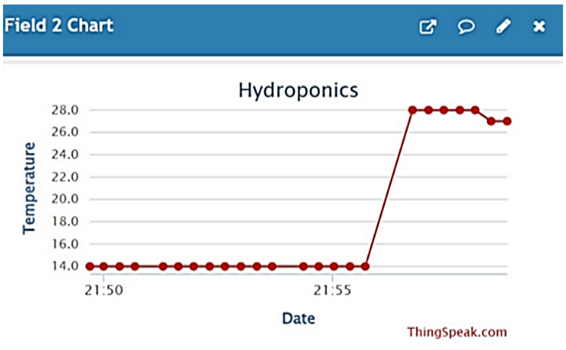

Figure 6. Variations in temperature

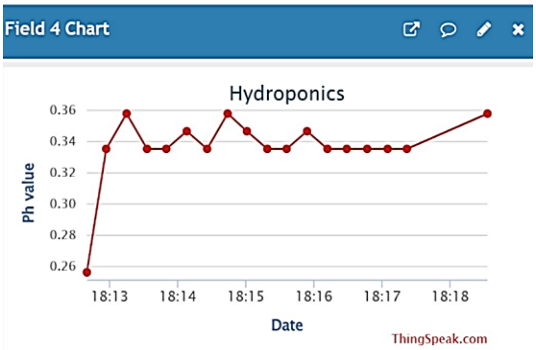

Figure 7. Variations in pH value

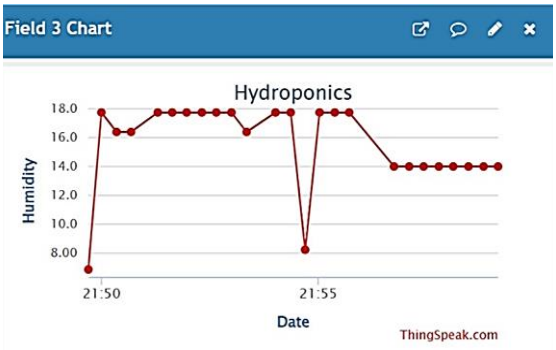

Figure 8. Variations in humidity

Table 1 compares the proposed NFT-based hydroponic system with other common hydroponic methods (like DWC, Aeroponics, and Drip systems) across key parameters such as water usage, nutrient efficiency, growth rate, and automation feasibility. NFT demonstrates superior performance in water and nutrient efficiency, fast plant growth, and ease of automation, making it ideal for smart farming. While some methods are simpler or cheaper, NFT offers a balanced solution with high productivity and sustainability for urban agriculture.

Table 1. Comparison of the methods used in this work with existing methods

Feature	NFT	Deep water culture (DWC)	Aeroponics	Drip system	Ebb and flow (flood and drain)	Kratky method
Water usage	Very Low (recycled)	Moderate	Very low	Low	Moderate	Low
nutrient efficiency	High (continuous circulation)	High	Very high	Moderate	Moderate	Low
Growth rate	Fast (oxygen-rich roots)	Fast	Very fast	Moderate	Fast	Slow
Automation feasibility	High (sensors and IoT-friendly)	High	Very high	High	Medium	Low
Oxygenation	High (thin film exposure)	High (air pumps required)	Very high	Moderate	Moderate	Low
Complexity	Medium (requires slope & flow)	Low (static water setup)	High (mist control needed)	Medium (timers needed)	Medium (pump control needed)	Very low (passive system)
Cost	Medium	Low	High	Medium	Medium	Very low
risk of system Failure	High (pump failure affects plants)	Low (backup air stones)	High (clogging risk)	Low	Medium (flooding risk)	Very low
Best for	Leafy Greens, Herbs	Lettuce, Herbs, Greens	High-value crops (strawberries, cannabis)	Tomatoes, Peppers	Mixed Crops (DIY Gardens)	Home gardeners

5. CONCLUSION

The IoT-enabled NFT hydroponic system presents a highly efficient, scalable, and sustainable approach to modern agriculture. By integrating real-time sensor-based automation, AI-driven analytics, and cloud-based monitoring, the system ensures optimal plant growth with minimal human intervention. Key parameters such as pH, TDS, temperature, and humidity are continuously monitored and adjusted, leading to improved resource utilization, higher crop yields, and reduced environmental impact compared to traditional farming methods. This smart hydroponic system addresses global challenges like water scarcity, land limitations, and unpredictable climatic conditions, making it particularly suitable for urban agriculture and controlled environment farming. The incorporation of IoT and AI enhances decision-making, allowing for predictive maintenance and remote management. Future advancements, including machine learning-based optimization, solar energy integration, and robotic automation, can further enhance system efficiency and accessibility. In conclusion, the proposed smart hydroponic system represents a significant step toward precision agriculture, offering a viable and sustainable alternative for food production in a rapidly urbanizing world. Its automation and intelligent monitoring capabilities make it a promising solution for increasing agricultural productivity while conserving vital resources.

FUNDING INFORMATION

No funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Varuna Kumara	✓				✓	✓				✓				
Akshatha Naik					✓						✓			✓
Fatima Tahsir		✓				✓		✓	✓	✓	✓	✓		
Sinchana Bommayya Devadiga	✓		✓	✓			✓			✓	✓		✓	✓
Vinitha Ramesh Naik		✓					✓		✓	✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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