

IoT-Based Smart NFT Hydroponic System for Automated Nutrient and Environmental Monitoring

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Abstract: Agriculture nowadays is facing many problems like population growth, reduction of cultivable land, climate changes and water scarcity. On the other hand, traditional agriculture based on soil is inefficient, costly and prone to environmental factors that adversely affect crop yield. Hydroponics is the most innovative idea proposed so far, but among all the systems available, the Nutrient Film Technique (NFT) has been found to be the most suitable for leafy vegetables because of its constant flow of nutrients and efficient use of resources. However, traditional hydroponic systems also have some disadvantages such as manual observation, inaccurate nutrient dose, and poor scalability. In this context, this study aims to develop a new approach using Internet of Things (IoT) and NFT hydroponics. This project uses NodeMCU ESP32 board to monitor the environmental dedicated sensors monitor environmental variables such as pH, electrical conductivity, water levels, humidity and lighting, and actuators manage pumps, valves and lighting equipment for improved resource management.

Keywords: Hydroponic, IoT, NodeMCU ESP32, Smart Farming, Sustainable Agriculture

I. INTRODUCTION

Hydroponic technology, a soil-free agricultural practice, is gaining prominence for revolutionizing crop production techniques. The research work uses the Nutrient Film Technique wherein pumps are employed to circulate shallow water continuously resulting in the highest availability of water, nutrients and oxygen to the plants.

Some of the issues associated with modern agriculture include increasing human population, decreasing amount of available arable land, changing climate, and water shortage. The current farming practices require intensive labor and resource inputs along with dependence on weather.

The application of hydroponics, especially with NFT technique, provides some benefits for cultivating leafy vegetables and herbs due to efficient utilization of nutrients and resources, but the current hydroponic technique has some disadvantages like need for manual control and maintenance, inaccurate dosing of nutrients, inefficient use of light sources, and scalability issues.

In this study, we combine the Internet of Things (IoT) technology and NFT hydroponics to design a smart farming system using the NodeMCU ESP32 board as a controller for regulating the sensors of various parameters and actuators such as pumps.

II. LITERATURE REVIEW

A. S. Agnal designed an automated indoor hydroponic system using Internet of Things sensors and connectivity for monitoring temperature, humidity, pH level, nutrient levels, and sunlight. The system offers real-time monitoring and



automation for increased yield and efficiency, though no machine learning based optimizations are involved. Our NFT system uses NodeMCU ESP32 for cost-effective and scalable automation with optimization of nutrient level management, specifically for leafy vegetables [1].

N. Luwes compared Decision Trees and K-Nearest Neighbor algorithms for brinjal crop growth prediction in NFT hydroponic systems, obtaining 88% accuracy with KNN. Their objective was to yield predictions. Our system uses real-time IoT-based automation through ESP32 with environmental management as compared to yield prediction [2].

C. Suresh and S. Selvabhuvaneswari used machine learning algorithms such as Random Forest and the internet of things for web-based monitoring of hydroponics, including irrigation and lighting optimization through prediction. Our NFT system involves real-time IoT-based automation with cost-effectiveness and nutrient regulation [3].

K. Pavan employed DT and KNN algorithms for yield prediction in NFT systems, attaining an accuracy of 88%, using Machine Learning techniques. IoT technology is the major emphasis of our technique in terms of monitoring, along with automation of environmental parameters [4].

P. Gourshettiwar and K. Reddy suggested an IoT-based technique, incorporating cloud notifications for detecting parameter deviation. Their technique enhances knowledge regarding deviations from parameter setpoints, whereas our proposed technique utilizes ESP32 to automate the process of pumping as well as supplying nutrients [5].

The paper by L. Ezhilarasan et al. discussed Vertical hydroponics along with IoT usage for space optimization and environmental parameters monitoring. Our paper mainly concentrates on flow of nutrients and monitoring, along with automation through ESP32 in NFT systems [6].

III. PROPOSED DESIGN

Conventional farming methods and simple hydroponics need constant human intervention to measure essential elements like pH, nutrient levels, temperature, and water volume. In practice, this usually results in inaccuracies, delayed response, over-watering, nutrient imbalance, and poor production results. Smaller farms also have a harder and more costly time maintaining ideal growing conditions.

To overcome the above issues, we propose a new IoT-enabled NFT (Nutrient Film Technique) Smart Farming System that will automatically monitor and control several key parameters. Our system has several sensors that will send live information to the central microcontroller (ESP32). All collected data will be stored in the cloud (Firebase) and accessed through a mobile/web application. Our solution also involves automatic regulation using relay switches and a predictive algorithm based on historical data to determine the stability of the system.

The proposed design makes it possible to continuously monitor pH levels, TDS levels, water and air temperatures, humidity levels, illumination, and water levels. Whenever any one of these parameters goes out of its optimum limits, actuators get triggered, and the user gets an alert message. It must be noted that the main objective behind designing such a system was to come up with a highly intelligent, automated, and sustainable way to cultivate crops using hydroponics.

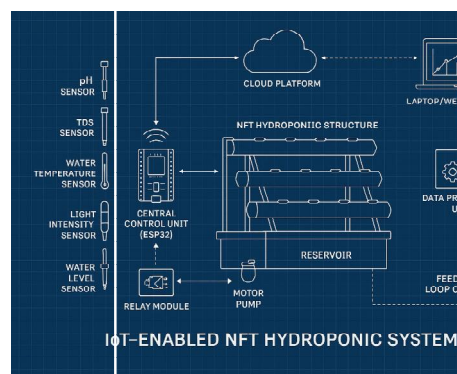


Figure 3.1 Blueprint of the proposed system.



The figure above (Figure 3.1) depicts an IoT-enabled NFT hydroponics setup, where various sensors, including pH sensor, TDS sensor, water temperature, light intensity, and water level sensors, transmit signals to the ESP32 controller board. The controller board operates the system using feedback control technique by switching on the relay and starting the operation of the pump. This ensures that the correct supply of nutrients is provided through NFT channels.

IV. ARCHITECTURAL DESIGN

Components & Modules

Sensors Module: pH sensor, TDS sensor, water level sensor, temperature/humidity sensor, light sensor

Actuators Module: Water pumps, nutrient pumps, grow lights, fans, relay modules

Processing Module: ESP32 microcontroller for data processing and actuators operation.

Communication Module: Wi-Fi (already embedded into ESP32) for communication with cloud.

User Interface Module: Mobile/Web application for remote data viewing and receiving notifications.

Data Flow

Sensors -> ESP32 receives data about parameters.

ESP32 compares received values with optimal ones.

Data is sent to Cloud -> to Mobile/Web app via Internet

If necessary, actuators are automatically turned on by the ESP32

ML-based algorithm checks stability of recent data -> generates alerts if necessary

Hardware + Software Blocks

Hardware Blocks: Sensors -> ESP32 -> Relayed controlled actuators -> Wi-Fi -> Cloud -> App.

Software blocks: Data acquisition -> Threshold checking -> Cloud communication -> Application dashboard ->

Stability analysis -> Actuators operation

Communication Layers

Physical Layer: GPIO/I2C/ADC interface between sensors and actuators and ESP32.

Network layer: Communication through Wi-Fi based on HTTP/MQTT protocol to Firebase Cloud.

Application Layer: Laptop/Web application.

Cloud Integration Structure

Data Storage: The Firebase Realtime Database is used for storing all the sensor inputs, actuator states, and historical data.

Visualization: Data Visualization happens using the Smart Farming app.

Control & Automation: ESP32 device can also be manually controlled through the app.

Analysis: Unsupervised machine learning algorithm works on the ESP32 or cloud for stability analysis.

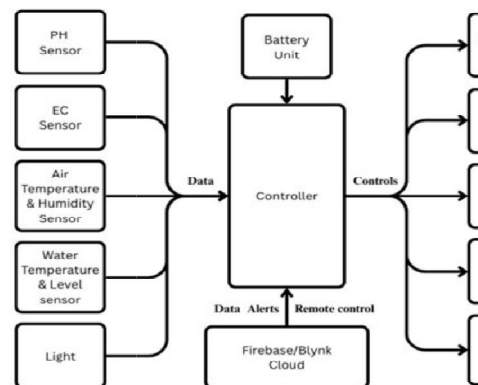


Fig. 4.1 Block Diagram



The block (Figure 4.1) diagram of the IoT-based NFT hydroponic system that was designed is presented in Fig. 4.1. Different types of sensors, such as pH sensor, EC sensor, air temperature and humidity sensor, water temperature and level sensor, and light sensor are used in order to measure the parameters of the nutrient solution and environment. The information from the sensors is transmitted to the controller that works with the help of a battery pack. The control signals for the circulation pump, dosing pumps, solenoid valve, and grow lights are generated in response to the data analysis performed by the controller. The whole system is associated with the Internet and can be controlled remotely via the Firebase/Blynk cloud platform. The outputs of the controlled processes are applied to the NFT hydroponic system that consists of tubes, net pots, and the reservoir.

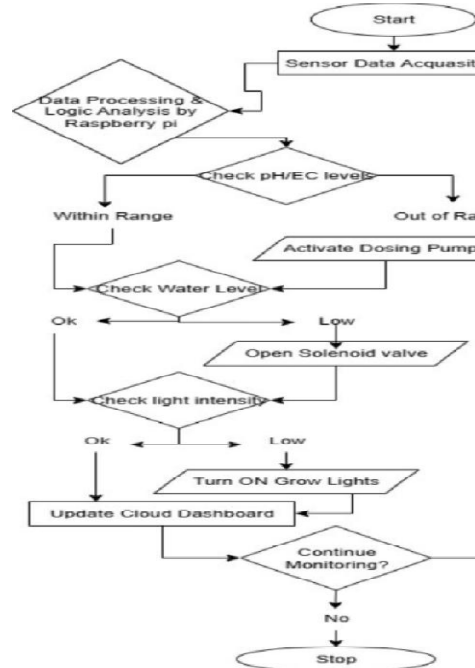


Fig. 4.2 System Flowchart

Figure 4.2 presents the complete flow diagram of the automation system for monitoring and control operations. As can be seen, the first step of this system involves the acquisition of information from sensors. Parameters like pH, EC, water level, and light intensity are acquired in this stage. After that, Raspberry Pi performs analysis and logical calculations based on data obtained. First, the system verifies the pH and EC readings. If they are in an acceptable range, the system continues its work; if not, dosing pumps are started to regulate nutrients' solution.

Then the water level check occurs. If the water level in the tank is low, the solenoid valve is opened; if sufficient, no operation is performed. After that, the check of light intensity takes place. If it is not sufficient, the grow lights are turned on.

Once all checks and operations are finished, the information is sent to the cloud dashboard. And finally a decision is made to continue monitoring.

V. MATHEMATICAL MODELING/DESIGN

The proposed IoT enabled NFT hydroponics model can be viewed as a sophisticated multi-parameters feedback control system which tries to provide the best possible growing conditions for the plants by constantly measuring different parameters, evaluating the errors and making corrective adjustments to them. It monitors EC (nutrient content), pH, water temperature, ambient temperature, humidity, lighting and water levels all of which are critical factors in agriculture and the environment.



Let the monitored parameter vector be given by:

$$S = \{pH, EC, T_w, T_a, H, L, WL\}.$$

where is

pH = Acidity/alkalinity of the feed solution

EC = Nutrient concentration (electrical conductivity)

T_w = Water temperature

T_a = Ambient air temperature

H = Relative humidity

L = Light intensity

WL = Reservoir water level

Each parameter has an optimum operating range defined as:

$$S = \{pH_{\min-\max}, EC_{\min-\max}, T_{w_{\min-\max}}, \dots\}$$

The control objective is to preserve:

$$S_{\min} \leq S(t) \leq S_{\max}$$

At all sampling times.

PH Regulation Model:

The absorption of nutrients and chemical imbalance caused the pH value to vary.

The deviation is computed by:

$$E_{pH} = pH_{\text{measured}} - pH_{\text{optain}}$$

Control Logic:

If $pH < pH_{\min}$ – Add base solution

If $pH > pH_{\max}$ – Add acid solution

Otherwise → No action

The correction time t_c is proportional to the magnitude of the deviation, i.e.,

$$t_c \propto |E_{pH}|$$

This allows for slow correction and no overshoot.

Model of Nutrient Concentration:

Electrical conductivity is a measure of the concentration of dissolved nutrients. It depends on plant uptake and dilution.”

We can estimate the rate of change as:

$$d(EC)/dt = -U + D - L$$

where: $S_1 =$

U = Rate of uptake of plant nutrients

D = Dosing rate

L = Loss or diluting factor

Control Strategy:

$$E_{EC} = EC_{\text{optain}} - EC_{\text{measurand}}$$

If $EC < EC_{\min}$ - Nutrient pump ON

If $EC > EC_{\max}$ - Dilution or addition of water

Else → Keep state

The correction process is performed for a limited time and re-checks the value after the stabilization delay.

Water Level Safety Model:

Water level decreases from evaporation and plant consumption.

$$d(WL)/dt = -C + R$$

where:



C = Consumption rate

R = Refill rate

Safety Logic:

If $WL < WL_{\text{threshold}}$:

Circulation pump OFF

Refill mechanism ON

If $WL \geq WL_{\text{optain}}$:

Resume normal operations

This avoids dry running and damage to hardware.

Lighting Optimization Model:

Total light available to the plants:

$$L_{\text{total}} = L_{\text{natural}} + L_{\text{artificial}}$$

Requirement:

$$L_{\text{total}} \geq L_{\text{required}}$$

Control Rule:

If $L_{\text{natural}} < L_{\text{required}}$:

$$L_{\text{artificial}} = L_{\text{required}} - L_{\text{natural}}$$

Else:

$$L_{\text{artificial}} = 0$$

This allows for energy-efficient illumination control.

Environmental Monitoring Model:

Temperature and humidity affect the rate of plant growth and the uptake of nutrients.

Error computation:

$$E_T = T_{\text{optain}} - T_{\text{measured}}$$

$$E_H = H_{\text{optain}} - H_{\text{measured}}$$

If the deviation is outside the pre-defined tolerance band, environment alerts are sent or cooling/ventilation mechanisms are activated.

Integrated Control Algorithm

At each sampling period, the system uses a sequential evaluation method:

Step 1: Get all the sensor data.

Step 2: Remove abnormal readings.

Step 3: Compare with threshold ranges

Step 4: Check safety condition (Water Level priority).

Step 5: Make nutrient and pH adjustment.

Step 6: Control lighting system

Step 7: Log data to cloud server

Step 8: Wait for delay of stabilisation.

Step 9: Repeat cycle

The algorithm ensures:

Minimal energy usage

Controlled dosing of nutrients

Reduction of parameter variation

Safe operation



Pseudocode:

```
Begin System
Load Optimal Parameters
Set Sampling Time Ts
WHILE System Active
  Read All Sensor Values
  Apply Noise Filtering

  // Priority 1: Safety
  IF Water_level < W1_min THEN
    Disable Circulation Pump
    Enable Refill Valve
    Send Alert
    Continue Loop
  End If

  // Priority 2: Nutrient Control
  IF |EC - Ec_opt| > Ec_threshold THEN
    Calculate Dosing_time
    Activate Nutrient Pump
    Wait Stabilization_time
  End If

  IF |pH- pH_opt| > pH_threshold THEN
    Apply Proportional Correction
    Wait Mixing_time
  End If

  // Priority 3: Environmental Stability
  IF Temperature Outside Range THEN
    Trigger Environmental Alert
  End If

  // Priority 4: Energy Optimization
  IF Light_intensity < Light_opt THEN
    Turn ON Artificial Light
  Else
    Turn OFF Artificial Light
  End If

  Upload Data To Cloud
  Wait Ts

End While

End System
```



VI. EXPECTED OUTCOME

The proposed IoT-based NFT hydroponics can provide stable, energy-efficient and automatic control of nutrients for controlled plant growth. In terms of the theoretical framework discussed earlier in the paper, the following results can be expected.

Stable Nutrient Regulation

The feedback-based monitoring mechanism is designed to keep:
pH within the optimum range (e.g., 5.5–6.5 for leafy vegetables)

Electrical Conductivity within predetermined limits of nutrient concentrations

The constant evaluation against thresholds and limited doses of corrections will stabilize the nutrients levels, which will support better nutrient uptake efficiency and plants stress reduction.

Improved Water Resource Management

The water level monitoring and refill logic is expected to:

Avoiding dry-run conditions of circulation pumps

Minimize unnecessary water waste

Ensure there is a constant flow of nutrient film through the NFT channels

This leads to efficient water utilization compared to the traditional soil agriculture.

Energy Optimization

The adaptive lighting control model ensures that artificial grow lighting is switched on only when natural light is insufficient. So, the system is expected to:

Cut down on energy consumption in general

Lower operational cost efficiency

Keep the same light for crops

Energy savings are achieved without compromising the plant growth requirements.

Environmental Stability

Monitoring temperature and humidity continuously is expected to:

Minimize environmental variation

Mitigate plant stress from sudden changes

Keep a controlled microclimate that is conducive for growth of plants.

Uniform crop development should result from less variance in environmental parameters.

Increased Crop Yield and Quality

By maintaining optimal physicochemical conditions during the growth cycle, the proposed framework is aimed to:

Boost nutrient absorption efficiency

Increase root oxygen in NFT channels

Biomass production increase

Grow reliable quality crops

Stable regulation of nutrients and environment directly influences the rate of photosynthesis and overall plant productivity.

Reduced Manual Intervention

The automated monitoring and correction mechanism will:

Reduce human oversight

Decrease the amount of labor needed

Enable remote monitoring with cloud integration

This increases scalability and makes the system suitable for urban and commercial hydroponic farming applications.

System Reliability and Safety

The priority-based safety mechanism, especially the water level protection logic, is expected to:

Don't break the hardware



Increase system life

Continuous operation Guaranteed

Its modular design also allows predictive analytics or AI-based optimisation modules to be integrated in the future.

Scalability and Practical Deployment Potential

The proposed architecture is both scalable and flexible. It can be generalized as:

Bigger commercial hydroponic farms

Vertical farming setups

Greenhouse environment control

The framework supports the integration of other sensors and automation modules without having to redesign the structure.

VII. CONCLUSIONS

The Proposed IoT enabled NFT hydroponic system effectively addresses the limitations of traditional soil based cultivation and simple hydroponic systems. Thanks to the application of sensors, automatic controls and cloud services, the system can guarantee an optimal management of vital parameters such as pH, electrical conductivity, water temperature, environment, light strength and water level.

Automated nutrient delivery, grow light adjustment and water-level protection will decrease human interaction and energy consumption. Cloud monitoring improves the accessibility of the system by allowing remote system monitoring and analysis.

Moreover, the designed system ensures efficient use of water and nutrients, good environmental control, as well as continual circulation of nutrients in the nutrient film layer. As a result, there is a promotion of healthier plant development and better performance of crops grown using hydroponic techniques.

In general, the presented solution confirms that a hydroponic farming approach based on IoT and employing a nutrient film technique is a promising technology that can be used in smart agriculture. Further improvements and optimizations will certainly enhance its prospects for success.

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