RESEARCH ARTICLE

RSP Science Hub

International Research Journal on Advanced Science Hub
2582-4376
www.rspsciencehub.com
Vol. 07, Issue 12 December

Check for updates

http://dx.doi.org/10.47392/IRJASH.2025.0120

Automated Herbal Hydroponics

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Article history
Received: 21 September 2025
Accepted: 22 October 2025
Published:26 December 2025

Keywords:
IoT, ESP8266, ThingSpeak, DHT11 Sensor, TDS Sensor, LDR Sensor, LCD, YOLOv11, ESP32-CAM.

Abstract
The proposed system introduces an intelligent hydroponics model that integrates Internet of Things (IoT) and Artificial Intelligence (AI) to enable automated, data-driven plant cultivation without the use of soil. The system employs an ESP8266 microcontroller for real-time monitoring of temperature & humidity, light intensity, and nutrient concentration using DHT11, LDR, and TDS sensors respectively. Sensor readings are displayed on LCD and transmitted wirelessly to the ThingSpeak cloud platform, which enables continuous visualization and remote supervision of environmental conditions. Based on ambient light levels, the controller automatically regulated LED grow lights through a relay module, while a constant-speed water pump ensures uninterrupted nutrient circulation. An ESP32-CAM module provides live video streaming of the plant, and a YOLOv11-based computer-vision model executes plant detection, size estimation, and growth assessment. Power management is achieved by 12-V supply with buck converters to maintain stable operation across all components.

1. Introduction

Modern agriculture faces the dual challenge of increasing for production while conserving natural resources. Traditional soil-based farming method often requires large areas of land and labor while being heavily dependent on climate and seasonal variations. Hydroponics, a method of cultivating plants in nutrient-rich water solutions without soil, has emerged as a sustainable and space-efficient alternative. However, conventional hydroponics systems demand constant manual supervision to maintain optimal environmental conditions like temperature, humidity, light intensity, and nutrient concentration. This dependence on human monitoring can lead to inconsistent growth results and reduced efficiency. With the advancement of internet of things (IoT), it has become possible to create intelligent agricultural systems capable of continuous monitoring and autonomous control. In this context, the proposed automated herbal hydroponics integrates IoT and Artificial Intelligence to automate plant cultivation and environmental management. The system employs an ESP8266 microcontroller to collect real-time data from DHT11 sensor for temperature and humidity, an LDR for light intensity, and TDS sensor for nutrient concentration. These parameters are transmitted to the ThingSpeak cloud platform for visualization and remote supervision. Based on the output of the sensors, the system will automatically turn on the LED lights through relay module and there will be continuous water in the circulation in the system for continuous nutrient supply for the plant To enhance monitoring accuracy, an ESP32-CAM module will provide live streaming of the plant. The captured images are further processed using a YOLOv11 deep learning model running on a local computer, which enables the real-time plant detection, size estimation, and growth assessments. This AI-driven analysis allows early identification of plant health issues, supporting more precise interventions. [1-3]

1.1. Related works

In recent years, hydroponics farming has gained significant attention as a sustainable alternative to soil cultivation, especially with the integration of IoT, automation, and AI-based control. Automation has also played a major role in advancing hydroponics. Jae Hyeon et al developed a low-cost IoT enabled system that maintained stable pH, temperature, and nutrient levels, addressing challenges in manual monitoring and improving growth efficiency (J. H. Ryu, 2025). Kushwala et al. proposed a compact urban hydroponics system using NodeMCU and cloud monitoring, offering precise environmental control suitable for small-space farming (Akshay Kushawaha, 2024). Rajendra and Rajauria explored innovative hydroponic methods for mini-tuber production, reporting improved yield, quality, and disease resistance through aeroponics-based systems (S. Rajendran, 2024). Heriansyah et al. further enhanced this concept by implementing an AI-based sensing framework that optimized nutrient control and ensured healthier plant growth compared to conventional methods (S. D. Putra, 2024). Affordable hydroponics systems have also emerged. The SMART GROW system by Kenny Yung Shin et al. presented an IoT-enabled with mobile app integration that improved regulation of pH, EC, and water levels in farming environment (K. K. Y. Shin, 2024). Lakshmi Priya introduced an AI- enabled hydroponic setup for Holy Basil cultivation, achieving high accuracy in plant health prediction and demonstrating the potential of AI in medicinal plant monitoring (G. L. Priya, 2023). IoT-driven automation continues to advance. Varuna Kumara et al. designed a smart hydroponic system enabling fully automated nutrient control and real-time monitoring, resulting in stable and efficient plant growth (Varuna Kumara, 2023). Machine learning applications were highlighted by Idoje et al., whose system effectively regulated environmental variables such as pH, humidity, and nutrient levels, and nutrient levels to optimize plant performance (Godwin Idoje, 2023). Rajaseger et al. developed a hydroponic monitoring system that uses image processing and an MLP classifier to automatically detect macronutrient deficiencies in chili plants, achieving highly accurate classification in real hydroponic environment (G. Rajaseger, 2023). Similarly, Vagisha et al. proposed an IoT-based smart hydroponic framework designed to counter reduced agricultural land availability through efficient indoor cultivation (Vagisha, 2023). [4-6]

2. Methodology

The methodology of the proposed Smart Hydroponics involves the integration of sensing modules, control circuitry, cloud connectivity, and AI -based monitoring. The system is designed to continuously monitor environmental parameters, automate plant support mechanisms, and analyze plant growth intelligently. The complete workflow is given below. [7-10]

2.1. Hardware Components

The system incorporates several electronic components and sensors that work together to enable real-time monitoring, automated control, and AI-based analysis. A brief overview of the major components is provided below.

- **ESP8266 NodeMCU:** The ESP8266 NodeMCU is a low-cost Wi-Fi-enabled microcontroller used as the central control unit of the system. It features GPIO pins for sensor interfacing, built-in Wi-Fi for cloud connectivity, and sufficient processing capability to handle continuous sensor acquisition and communication tasks.
- **ESP32-CAM:** The ESP32-CAM module combines a microcontroller with an onboard camera, enabling wireless video streaming. It is used to capture live plant images for further processing through the YOLOv11 model, supporting plant detection and growth estimation.
- **DHT11 Temperature and Humidity Sensor:** - The DHT11 sensor measures the surrounding temperature and humidity. It generates calibrated digital output and provides reliable environmental readings essential for assessing plant growth conditions.
- **Light Dependent Resistor (LDR):** - The LDR detects ambient light intensity. Its

resistance varies with the amount of light falling on it, enabling the system to determine when illumination is insufficient and automatically activate the LED grow lights using a relay module.

- **TDS (Total Dissolved Solids) Sensor: -** The TDS sensor is used to evaluate nutrient concentration in the hydroponic water. It outputs an analog voltage corresponding to the dissolved solid level, ensuring that the nutrient solution remains within the optimal range for plant growth. [11-13]
- **LED Grow Lights:** - LED grow lights provide artificial illumination required for plant photosynthesis. They are controlled automatically through a relay module based on LDR sensor readings, ensuring consistent lighting conditions.
- **Relay Module (5V):** - The relay module acts as an electronically operated switch. In this system, it controls the LED grow lights by responding to the light intensity measured by the LDR.
- **12V DC Water Pump:** - A 12V diaphragm pump circulates nutrient-rich water throughout the hydroponic setup. Continuous operation ensures proper mineral distribution and oxygenation, both critical for plant growth.
- **LM2596 Buck Converter:** - The LM2596 DC-DC buck converter provides regulated 5V and 3.3V power outputs from the 12V supply. This ensures stable power delivery to the ESP8266, Sensors, and the ESP32-CAM.
- **16x2 I2C LCD Display:** - The I2C module displays real-time sensor readings such as temperature, humidity, light intensity, and TDS values.
- **Glass container:** - A glass container is used as medium to store the plant and monitor its growth.

2.2. Software Components

The implementation of the automated hydroponics system relies on multiple software tools and libraries that enable microcontroller programming, cloud communication, and AI-based monitoring. A concise overview of the software components is presented below.

- **Arduino IDE:** - The Arduino IDE is used to develop, compile, and upload programs to ESP8266 and ESP32-CAM modules. It provides a simple interface for writing embedded C code and supports the communication between the sensors and the NodeMCU.
- **Python 3.8 with PyCharm IDE:** - Python serves as the primary programming language for processing the video stream captured by the ESP32-CAM. PyCharm is used as the development environment for running the YOLOv11 model and executing image processing task such as plant detection and size estimation.
- **ThingSpeak Cloud Platform:** - ThingSpeak is employed for cloud-based data storage and visualization. It receives real-time sensors readings from the ESP8266, plots them on graphical dashboards, and enables remote monitoring of environmental parameters.
- **YOLOv11 Deep Learning Model:** - The YOLOv11 is used for AI-based plant detection and growth analysis. It processes live video frames from the ESP32-CAM, identifies plant regions, and calculate bounding box dimensions to estimate plant growth over time.
- **OpenCV library:** - OpenCV is a Python-based computer vision library used to handle image frames, preprocess video input, and interface with the YOLOv11 detection model. [14-15]
- **Required Arduino and Python libraries**: - Few of the libraries are used to simplify communication and sensor handling such as DHT.h, Wire.h, LiquidCrystal_I2C.h, ESP8266WiFi.h in Arduino and OpenCV-python, numpy, ultralytics in python.

2.3. System Architecture

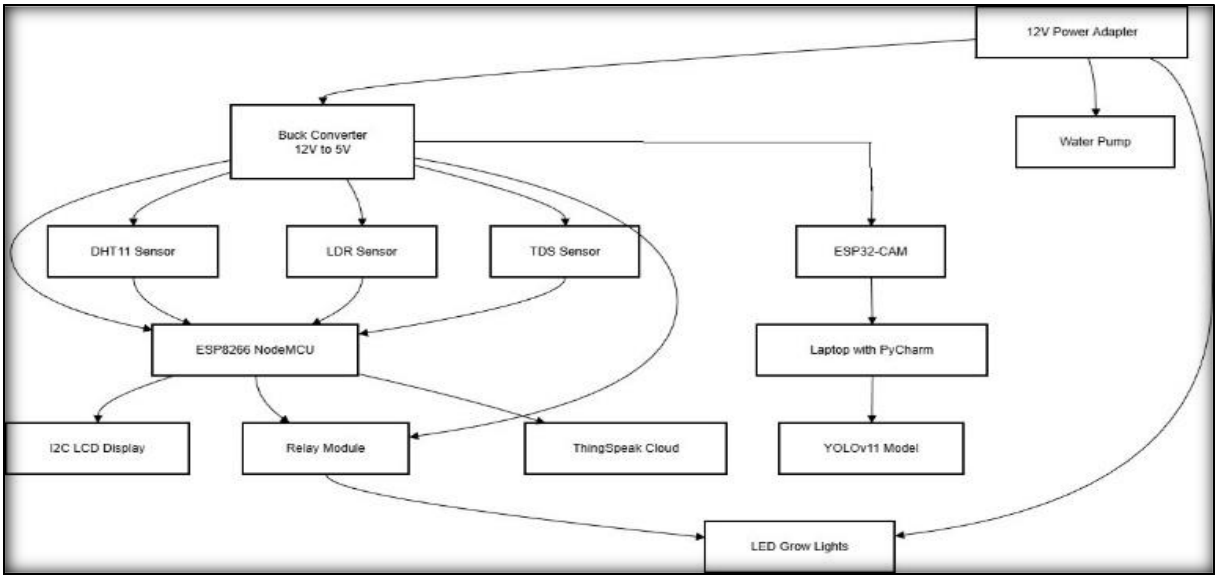
- The overall architecture of the system is depicted in Figure 1 and consists of interconnected sensing, control, and monitoring modules. A 12V supply powers the pump and LED grow lights, while LM2596 buck converters deliver regulated voltages to the sensors and microcontrollers.
- The ESP8266 NodeMCU serves as the main

controller that acquires data from the DHT11, LDR, and TDS sensors. These data values are displayed on an I2C LCD and are simultaneously uploaded to the ThingSpeak cloud through the Wi-Fi for remote monitoring.

- For visual assessment, an ESP32-CAM provides live video of the hydroponic unit. These frames area analyzed on a laptop using YOLOv11 computer vison model to detect plants, estimate their size, and monitor growth patterns.

2.4. Hardware Implementation

- The hardware implementation of the system is scattered around the ESP8266 NodeMCU, which interfaces with multiple sensors, a relay module. A pump, and the power regulation unit. As shown in Figure 2, each component is connected through designated GPIO pins to ensure reliable data acquisition and actuator control.
- The DHT11 sensor is connected to digital pin D5 of the ESP8266 to measure temperature and humidity. The LDR sensor's analog pin A0 is interfaced to the digital pin D0 of NodeMCU, allowing the controller to detect variations in ambient light intensity. The TDS sensor is also interfaced through an analog channel A0 to estimate nutrient concentration in the hydroponic solution.
- A 16x2 I2C LCD's SCL and SDA is connected to pins D1 and D2 respectively, utilizing the SDA and SCL lines for serial communication, which reduces the wiring complexity. The relay module is driven through the pin D6 of the ESP8266 and controls the LED grow lights, ensuring automated illumination based on LDR readings.
- The water pump is powered directly from the 12V supply and operates continuously to maintain nutrient circulation. The entire system is supplied by a 12V adapter, and the power is regulated using LM2596 buck converter. The converter is connected to the NodeMCU providing stable 5V and 3.3V outputs, preventing voltage fluctuations and ensuring safe component operation.
- This modular hardware arrangement allows seamless communication between sensing, control, and actuation units, creating a stable and efficient hydroponics system. Figure 1 shows Methodology Block Diagram of Automated Herbal Hydroponics



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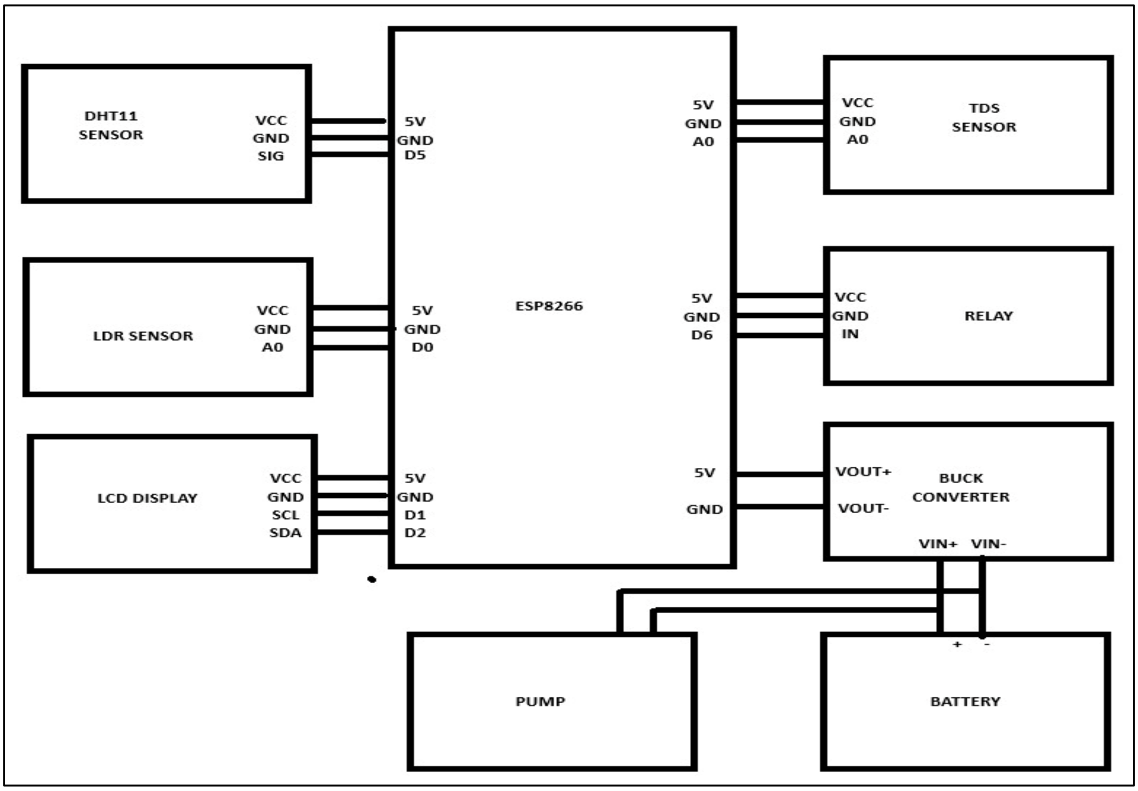

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2.7. Software Implementation

The software implementation is divided into two major processes:

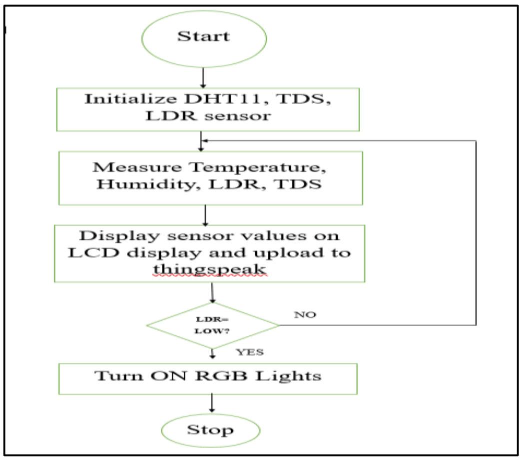
- Sensor data acquisition and IoT-based automation using ESP8266.

- AI-based plant monitoring using ESP32-CAM and YOLOv11 model.

Both workflows are illustrated in the flowcharts shown in figure 3A and 3B. The ESP8266 is programmed using the Arduino IDE, which supports embedded C development. Essential libraries such as DHT.h, LiquidCrystal_I2C.h, and ESP8266WiFi.h are used to interface sensors, control the display, and establish cloud connectivity. As shown in Figure 3A, the program begins with the initializing all sensor modules, including DHT11, TDS, and LDR sensor. In a continuous loop, the microcontroller reads real-time values from each sensor and displays them on the I2C LCD. ESP8266 uses a non-blocking loop to ensure continuous sensor updates without delays. The acquired data are then uploaded to the ThinkSpeak cloud using an HTTP POST request with API keys, enabling remote monitoring and graphical visualization. A conditional routine checks the LDR value; if the light intensity falls below a predefined threshold, the relay is activated to turn on the RGB grow lights. This creates an automated lighting control mechanism that maintains consistent illumination for plant growth. The second flowchart, Figure 3B, represents the machine learning and image – processing workflow. The ESP32-CAM continuously streams video frames to a python script running on a laptop. The script uses Open CV for frame extraction and a YOLOv11 deep learning model for object detection. The software pipeline begins by initializing the camera stream and loading the YOLOv11 model. Each captured frame is processed to determine whether a plant is present. If detected, a bounding box is generated and its area is calculated to estimate plant size or growth progression. If no plant is detected, the system continues capturing frames until a valid detection occurs. YOLOv11 interference is performed locally on a laptop to reduce load on the ESP32-CAM.

Algorithm: Plant Detection Using YOLOv11 and ESP32-CAM

- Step 1: Initialize ESP32-CAM stream URL, load YOLOv11 model, and set confidence threshold.
- Step 2: Start a background thread to continuously capture frames from the ESP32-CAM.
- Step 3: In the main loop, read the latest frame and prepare it for processing.
- Step 4: Perform YOLOv11 interference to detect plants in the frame by considering the width, height of the bounding box in pixels.
- Step 5: For each detection, extract bounding box coordinates, consider x1, y1 to be the top-left corner and x2, y2 to be the bottom-right corner of the box.
- Bounding Box Width=x2-x1
- Bounding Box Height=y2-y1
- Bounding Box Area (in pixel) = Width x Height
- Then consider the class label, confidence, and compute the area.
- Step 6: Annotate the frame with bounding boxes and detection information.
- Step 7: Display FPS, detection status, resolution, and summary details on the output window.
- Step 8: Continue processing until the user exits the program, then release the resources.



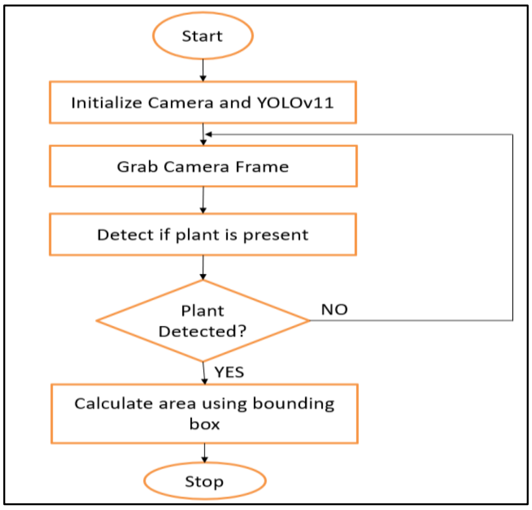


Figure 3 Software Flowcharts
A ESP8266-based sensor monitoring workflow
B YOLOv11-based plant detection workflow

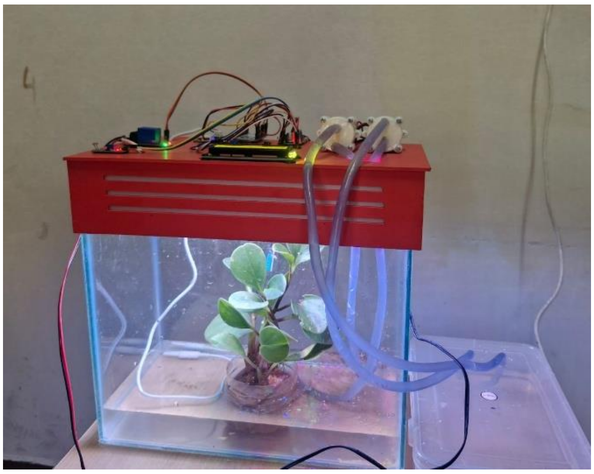


Figure 4 Hydroponics Model Setup

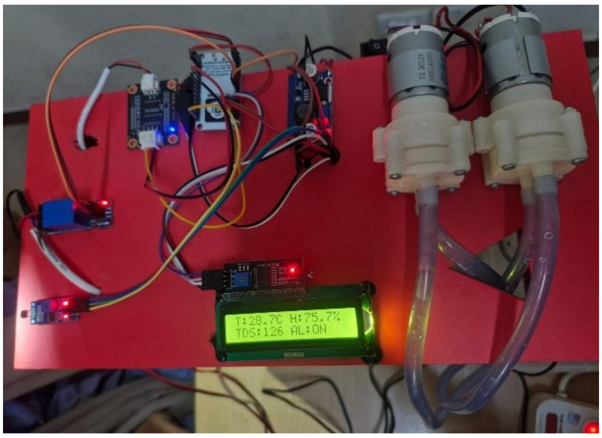


Figure 5 LCD showing the data display

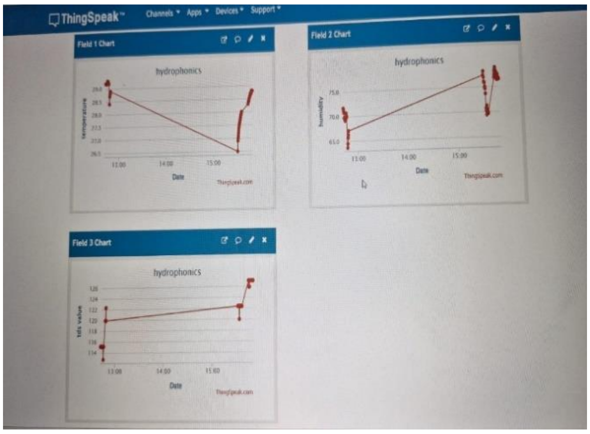


Figure 6 Output Graphs from Thing Speak Cloud

2.8. Cloud Integration

ThingSpeak is used as the cloud platform for visualizing sensor data. Each parameter is stored in dedicated fields and displayed fields and displayed on dynamic graphs. This allows remote observation of environmental variations and long-term tracking of system performance. The cloud platform also supports real-time alerts and data logging for research analysis.

3. Results and Discussions

3.1. Results

The results obtained from the developed smart hydroponics system are presented in this section. The performance of the sensing modules, cloud monitoring interface, and YOLOv11-based plant detection model was evaluated through a series of controlled observations. Figure 4 shows the complete physical hydroponics model developed for this study. The system includes all the hardware components with the power regulation circuits. The assembled prototype served as the experimental platform for collecting sensor data and plant image. Figure 5 shows the real-time readings obtained from DHT11, TDS, LDR sensors on 16x2 I2C LCD. It displays the updated values continuously. Figure 3 shows Software Flowcharts A ESP8266-based sensor monitoring workflow B YOLOv11-based plant detection workflow Figure 6 illustrates the cloud visualization of the sensor data plotted on the ThingSpeak platform through Wi-Fi. The data will be uploaded every 2 seconds and includes temperature, humidity, and nutrients presence in the water. Figure 7 shows the output of the YOLOv11 model, where the plant has been successfully detected using a bounding box. The annotated frame displays the class label, confidence score, and calculated area in pixel units, indicating that the AI model can accurately identify plant presence and estimate the growth using bounding box dimensions. The environmental parameters recorded for five different hydroponics plants are summarized in the Table 1. These values represent the typical temperature, humidity, nutrient concentration, and light wavelength ranges. Self-calibration was performed to establish reference thresholds for interpreting the YOLOv11 detection results shown in Table 2. Since the ESP32-CAM was kept in a fixed position, multiple images of healthy and unhealthy plant samples were captured under identical light conditions. The bounding box generated by YOLOv11 model were recorded and compared to create baseline ranges. Healthy plants consistently produced larger bounding box areas due to fuller leaf density, while stressed or under-developed plants showed significantly smaller pixel areas. These calibrated values were then used as decision thresholds to differentiate normal growth from potential issues during real-time monitoring. Table 1 shows Hydroponic Growth Conditions for Selected Plant Species

Plant	Temperature (°C)	Humidity (%)	TDS (ppm)	Light/Wavelength
Baby Rubber Plant (Peperomia obtusifolia)	20-26°C	50-70%	350-500 ppm	450-470 nm (Blue)+650-660 nm (Red)
Spinach (Spinacia oleracea)	20-24°C	60-75%	700-1000 ppm	450 nm (Blue dominant)
Lettuce (Lactuca sativa)	18-24°C	50-60%	560-840 ppm	450-470 nm (Blue) + 630–660 nm (Red)
Basil (Ocimum basilicum)	20–26°C	50–65%	1000–1400 ppm	450–480 nm (Blue) + 640–660 nm (Red)
Mint (Mentha arvensis)	18–24°C	60–70%	800–1000 ppm	450–470 nm (Blue) + 660 nm (Red)

Table 1 Hydroponic Growth Conditions for Selected Plant Species

3.2. Discussion

The environmental data indicate that the system maintained stable temperature and humidity levels suitable for hydroponics growth. Differences in TDS requirements across plants, as shown in Table 1, reflect their physiological needs herbs such as basil required higher nutrient strength, while leafy vegetables like lettuce and spinach performed better under moderate TDS levels. The use of blue-red LED wavelengths supported uniform leaf development. Table 2 shows Self Calibration Results for YOLOv11 Pixel-Area Interpretation

Table 2 Self Calibration Results for YOLOv11 Pixel-Area Interpretation

Plant Condition	Bounding Box Area (px²)	Interpretation
Healthy (Good)	100,000-200,000	Plant growing well
Moderate	80,000-100,000	Slight Stress
Poor (Unhealthy)	< 80,000	Limited growth

The YOLOv11 calibration results in the Table 2 show that bounding- box area is a reliable indicator of plant growth when the camera position is fixed. Healthy plants consistently exhibited larger bounding-box regions due to wider leaf spread and denser foliage, whereas stressed plants produced smaller or irregular areas. This demonstrates that pixel-based area analysis can visually represent growth trends and detect early signs of poor growth. Clear correlations were observed between the sensor trends and AI outputs. Drops in TDS or inadequate light intensity were often followed by a reduction in bounding box area, while adjustments-such as LED activation led to noticeable recovery in growth. This confirms that combining sensor logs with visual analytics provides a more complete understanding of plant health. Overall, the system improves hydroponic management by delivering automated lighting, real-time clod monitoring, and early AI-based detection of growth variations. The integration of IoT sensing and computer vision enhances accuracy, reduces manual supervision, and supports timely corrective actions in controlled farming environments.

Conclusion

The study confirms that maintaining precise control over environmental parameters and continuously monitoring plant growth are critical challenges in hydroponics system. The results demonstrated that fluctuations in temperature, humidity, TDS, and light intensity directly influenced plant development, while the discussions validated that these variations could be reliably detected through both sensor data and AI-based visual analysis. The YOLOv11 model, supported by self-calibration, accurately reflected differences in plant health through bounding-box area measurements, confirming that computer vision can effectively identify early signs of stress that sensors alone may not capture. Thus, the integrated IoT-AI approach successfully addresses the problem of limited visibility and delayed detection in conventional hydroponic monitoring. Beyond addressing the core monitoring challenges, the system also enhances decision-making by combining real-time cloud logs. Automated lighting control helped maintain consistent growth conditions, while the camera-based assessment provided an additional layer of reliability by visually confirming plant health trends. This dual-layer approach demonstrates that intelligent hydroponics systems can improve efficiency, reduce manual supervision, and support more stable plant development. Overall, the work establishes a strong foundation for data-driven and AI-assisted hydroponics cultivation, offering a practical and scalable solution for modern precision agriculture.

Acknowledgment

The authors would gratefully acknowledge the support of the ECE department for providing laboratory facilities and resources required for successful implementation. We extend our gratitude to all faculty members and technical staff for their timely assistance and cooperation. Finally, we thank our project teammates for their collaboration and contributions in completing this work.

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