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Automated Nutrient Management and Growth Monitoring in Urban Farming using a Low-Cost ESP32 IoT Platform

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***Abstract*— More people moving to cities brings big problems for old style farming. It calls for new ways to grow food right where folks live. Growing plants without soil, like in hydroponics, looks like a good option. Adding tech makes it even better. This work shows how we built a cheap setup that can grow bigger. It uses the Internet of Things for handling nutrients on its own and checking plant growth all the time in city hydroponic setups. We based the whole thing on an ESP32 chip that saves energy. It acts as a smart spot on the edge. The chip grabs info from sensors that measure pH, heat, and nutrient amounts. It runs a loop to control things right away without help. It also sends data up to a cloud system for keeping records and looking it over. Spreading things out like this cuts costs and uses less power than setups with full computer boards. We made a phone app too. It lets users see health stats for plants from far away. They get warnings when needed. This makes exact farming easier to reach. Our setup proves it works well and does not cost much. It helps city growers and home users. Automated hydroponics gets simpler this way. It aids steady food making in busy places.**

***Keywords*— Internet of Things (IoT), Hydroponics, ESP32, Urban Farming, Cloud Computing, Precision Agriculture.**

I. INTRODUCTION

Food systems around the world sit at a tough spot now. Population keeps growing. Weather changes hit regular farming hard. We need food that lasts, bounces back, and comes from nearby spots. This feels urgent in packed cities. Supply lines stretch far there. They break easy. Tech steps in to help grow food near where people eat it.

Controlled farming in set spaces, like hydroponics, steps up strong here. It breaks free from needing land or seasons. You grow fresh stuff in custom spots. Control comes exact on nutrients, water, and surroundings. Plants speed up. Yields go higher than old farm ways. Hydroponics forms a key part for city growing ahead.

Automation and IoT data make hydroponics work way better. Lots of studies show smart versions can happen. Still, high prices and tricky hardware block wide use. Many designs lean on single board computers. Those handle a lot. But each one costs plenty. They pull big power too. That makes scaling or home tries hard.

We bring in a fresh IoT setup here. It costs less and opens up exact hydroponics for city use. The main part is our spread out design around the ESP32 chip. That low power thing works as a smart edge spot. It handles two big jobs. One is full auto nutrient control. The other is steady growth checks without touching plants. Light edge gear does real time work. Cloud handles data bunching. This gives a solid cheap frame for new farmers.

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To hit these goals, we tied in sensors run by a smart control code on the ESP32. The code keeps pH and nutrient strength in the solution just right. That matters a ton for plant wellbeing. Most times folks do it by hand. Our growth watch mixes surrounding data with water level tracks that do not bother over time. The phone screen shows this easy. The system runs main steps on auto. It gives users real tips too. This links pro farm tech to easy city growing

II. RELATED WORK

The growing interest in smart agriculture has led to a plethora of research focusing on automating hydroponic systems. This section reviews several key contributions in this domain, identifying their methodologies and highlighting their respective limitations, thereby establishing the unique contribution of our proposed ESP32-based platform.

Early work, such as that presented in [2], focused on monitoring the pH values of nutrient solutions, noting deviations from optimal ranges. While identifying a critical environmental parameter, this research acknowledged the high cost and limited usability of commercial pH monitoring modules, which remains a barrier to widespread adoption.

Similarly, the study in [3] delved into algorithms for optimizing tomato growth across various Californian regions, employing a node-based data collection system. However, a significant limitation identified was the substantial manual effort required for daily data collection and subsequent relaying to the processing nodes, undermining the goal of full automation.

Advancements in image processing for agricultural applications were explored in [4], which developed an intelligent aquaponics system capable of diagnosing leaf infections through image analysis, utilizing camera modules connected to a Raspberry Pi. The core limitation here was the reliance on a restricted dataset (50 samples) for diagnostic classification, suggesting a lack of robustness for broader application with custom datasets. Furthermore, the use of a Raspberry Pi, while capable, contributes to a higher power footprint and per-unit cost, which our work seeks to mitigate.

Regarding data analysis and feature selection, the IGA-ELM algorithm proposed in [5] demonstrated a reliable method for feature selection with multi-level simulation. However, its observed efficiency in selecting only 34.5% to 45.26% of relevant features, thereby producing a limited subset for subsequent model analysis, indicates room for improvement in comprehensive data utilization for predictive control.

Several projects have focused on web-based simulation and control. For instance, [6] presented a web-simulated hydroponics monitoring system with solenoid valves for nutrient solutions and water systems. A critical drawback noted was the insufficiency of the water motor, leading to unstable environments, and unreliable temperature, humidity, and pH sensing, resulting in inaccurate control. Moreover, the lack of testing with diverse nutrients for a wider variety of plants limited its general applicability.

Broader insights into the benefits of hydroponics for sustainable agriculture were provided by [8], which highlighted its positive response to conservation agriculture and potential for high-rise urban farming, especially under tropical climates with solar energy. While valuable, the observation that such benefits might be restricted to specific crop genera and climatic conditions points to the need for more adaptable and generalizable systems.

Cost-effective automation was a focus of [10], developing a LABVIEW-based system. Its primary limitation was the high cost associated with National Instruments (NI) hardware required for data acquisition (DAQ), making it less accessible for budget-conscious projects.

Similarly, [11] examined agricultural sustainability and intensive production, but was constrained by a restricted dataset for cross-country comparisons of vertical or hydroponics-backed farming policies, with insufficient emphasis on developing nations.

Finally, research in [13] delved into the chemical treatment and acquisition of nutrients in hydroponic solutions, identifying various chemical reactions (e.g., rainfall, precipitation, complexity) that can significantly affect nutrient availability. While crucial for understanding the science, this work underscores the need for intelligent monitoring and adaptive control systems that can counteract these chemical instabilities, a challenge often overlooked in hardware-centric designs.

In summary, while existing research has made significant strides in various aspects of smart hydroponics, common limitations persist, including high hardware costs (often due to SBCs), insufficient automation, reliance on limited datasets, and a lack of focus on energy efficiency and broad scalability for diverse urban farming scenarios. Our proposed ESP32-based IoT platform directly addresses these gaps by offering a highly cost-effective, energy-efficient, and scalable solution for automated nutrient management and growth monitoring, designed to be accessible for widespread urban adoption.

III. HYDROPONICS CULTIVATION TECHNIQUES AND CRITICAL PARAMETERS

Thing is, getting a handle on the different hydroponic cultivation methods and what really influences them matters a lot. It helps you see why certain design choices come into play in an automated setup. This section covers some of the main hydroponic techniques. It also looks at the key parameters that call for exact control to support the best plant growth. Pretty much, it highlights how an IoT platform steps in to improve how well these techniques perform.

A. Common Hydroponic Techniques

- Various hydroponic systems fit different kinds of plants and different scales of operation. The design of our system stays flexible. It handles the main parameters that show up across most of these methods.
- Nutrient Film Technique (NFT). In this setup, plants grow inside channels. A thin, recirculating layer of nutrient solution runs over their roots. The method saves water because of the recirculation. It also gives great oxygenation right at the root area. This approach works especially well for quick-growing leafy greens. Think lettuce, spinach, and herbs. The real trick comes in keeping that film steady and thin. You also need spot-on nutrient levels. Automated monitoring and dosing make a big difference here.
- Deep Flow Technique (DFT). People sometimes call this Deep Water Culture (DWC). Roots sit submerged in a bigger reservoir of nutrient solution. Unlike NFT, which needs constant pumping, DFT uses air stones to add oxygen to the still nutrient bath. The technique feels solid. It suits a broader mix of plants. That includes ones with longer growth periods. For DFT, the main issues involve steady pH, EC, and oxygen in that large water volume. Automated systems prove essential for keeping things healthy over time.
- Dynamic Root Floating Technique (DRFT). This method pulls from both NFT and DFT in a flexible way. Roots get dipped into nutrient solution now and then. The water level often rises and falls. That setup lets roots take in nutrients for a bit. Then they get air exposure for oxygenation. Timing those cycles just right matters for plant health. Duration counts too. Microcontrollers like the ESP32 offer programmable control that fits perfectly.

B. Critical Aspects for Plant Growth Management

- No matter the technique, hydroponics success depends on handling several environmental and nutritional factors with care.
- Growing Media. Hydroponics skips soil entirely. Still, inert media like rockwool, coco coir, or perlite often provide support for plants. The media choice impacts root aeration. It affects moisture holding and pH buffering too. Monitoring the whole system, not just the media, makes sure plants get what they need.
- Nutrient Management. This stands out as key in hydroponics. Plants pull all their macro and micronutrients straight from the water solution. In closed systems, nutrient makeup shifts over time. Plant uptake and water evaporation cause that. Without automated checks on Electrical Conductivity (EC) and pH, plus adjustments, problems build up. Imbalances lead to nutrient lockout or toxicity. pH swings can halt growth or even kill plants. The ESP32 platform tackles this head-on. It allows ongoing monitoring. It also enables exact dosing of nutrients. That stops buildup or shortages.
- Interaction of Plants and Pests or Diseases. Hydroponic systems run cleaner than soil farming in general. They still face risks from pests and diseases. The controlled setup in smart hydroponics brings real benefits though. Optimal nutrient profiles boost plant immunity and strength. That can make them tougher against typical threats. Tracking parameters like humidity helps too. It cuts down on chances for fungal issues.

IV. SYSTEM ARCHITECTURE

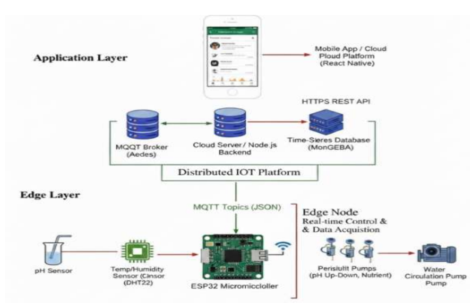


Fig 1. System architecture diagram

A. Module Description

- ESP32 Microcontroller: The core of the edge device is the ESP32-WROOM-32 module. This microcontroller was chosen for its dual-core processor, integrated Wi-Fi and Bluetooth capabilities, and extensive general-purpose input/output (GPIO) pins, making it ideal for interfacing with multiple sensors and actuators simultaneously. Its low power consumption is critical for creating an energy-efficient system.
- Sensing Array: A suite of sensors is used to continuously monitor the hydroponic environment, sending analog readings to the ESP32 for processing.
  - EC Sensor (Electrical Conductivity): This sensor is crucial for hydroponics as it gauges the volumetric content of dissolved mineral salts within the nutrient solution. It measures the electrical conductivity of the water, which directly correlates with the concentration of nutrients available to the plants. As plants consume nutrients or water evaporates, EC changes, signaling the need for adjustment.
  - Temperature & Humidity Sensor (DHT22): This sensor accurately measures both the ambient air temperature, operating at a range of -40 to 80°C with a ±0.5°C accuracy, and humidity (0 to 100% with 2-5% accuracy). These parameters are vital for plant transpiration rates and overall environmental control.
  - pH Sensor (Generic): An industrial-grade pH probe, typically interfaced with an amplifier board, measures the hydrogen-ion activity in water-based solutions. The measuring electrode detects changes in pH, while a reference electrode provides a stable comparison. The ESP32 processes the millivolt signal from the sensor to display pH units (on a scale of 0 to 14), which is critical to maintain within the optimal 5.5 to 6.5 range for most hydroponic plants.
  - Ultrasonic Sensor (HC-SR04): This sensor measures the distance to an object using ultrasonic sound waves and has a sensing range of 0 to 400 cm. In our system, it is deployed to accurately monitor the nutrient solution level within the water reservoir, ensuring critical alerts for low water conditions.
- Actuator Assembly: The system uses several actuators to autonomously manage the environment, controlled directly by the ESP32.
  - Peristaltic Pumps: Three separate peristaltic pumps are used for precise, low-volume dosing. These are responsible for adding pH Up solution, pH Down solution, and a concentrated nutrient mix into the reservoir, triggered by control signals from the ESP32.
  - Water Circulation Pump: A submersible 5V DC pump ensures that the nutrient solution is continuously mixed and circulated, preventing nutrient settling and ensuring consistent root exposure.

B. Software and Communication Protocol

The software works in a modular way. It keeps the real-time control logic separate from data management and the user interface.

- Edge Firmware and Process Controller (PID). They program the ESP32 with the Arduino framework in C++. The firmware includes the main Process Controller. This part takes in real-time sensor readings. It uses user-selected plant profile templates. These templates set target humidity, water level, pH values, and EC or nutrient concentration. A Proportional-Integral-Derivative controller algorithm runs right on the ESP32. It figures out the error e(t) as the gap between the desired setpoint (SP) and the process variable (PV). The PID controller takes that error and creates corrective PWM signals. These signals control the peristaltic pumps for pH and nutrient balancing. They also handle other parts, like a water circulation pump if needed. The ESP32 keeps processing the current and target states of the system. It checks changes against what users want. Figure 1 shows the detailed control flow.
- Communication Protocol (MQTT). They use MQTT for communication between the ESP32 edge node and the cloud server. MQTT stands for Message Queuing Telemetry Transport. Its lightweight design and publish-subscribe setup cut down on network bandwidth. It still ensures messages get delivered reliably, even with spotty connections. The ESP32 sends data to specific topics. For example, one might be hydroponics/unit1/ph. The server subscribes to those topics.
- Cloud Backend (HTTPS Server). The cloud backend runs as an HTTPS server. It uses Node.js and the Express.js framework. This setup handles data from the ESP32 through MQTT. It processes the data and stores it in a MongoDB database. MongoDB fits well for the
- dynamic, JSON-like structures from IoT devices. The backend offers secure REST APIs. The mobile app can use these endpoints to send commands or pull real-time and historical data. They use JWT for secure access to the APIs. JWT means JSON Web Tokens. This keeps data safe and protects user privacy.

➢ Front-End Module (Mobile Application). They built a cross-platform mobile app with React Native and a metro bundler. It has strong user authentication and secure login, maybe through OAuth or Firebase. The app sends in-app notifications for timely updates on the system's real-time status. It also includes localization. Users can switch to languages like Hindi, English, or Tamil. This makes the app more accessible and keeps users engaged.

Fig 2. Front end module screenshot

C. Methodology

Users usually start by picking a plant profile template from the categories we have set up. That template hands over the ideal setpoint values for the specific plant they want to grow. The key ones include temperature, water level, and pH value. Each profile keeps these settings unique to fit the plant just right. After the setpoints come in, the PID controller starts up on the ESP32 microcontroller. It pulls in the current environmental readings from the sensors. Then it works out the error by checking how far off things are from the targets. Based on that error, the controller fine-tunes the inputs going to the actuator drivers. We adjusted their sensitivity through the KP, KI, and KD constants. The whole setup keeps looping like this throughout the plant's growth period.

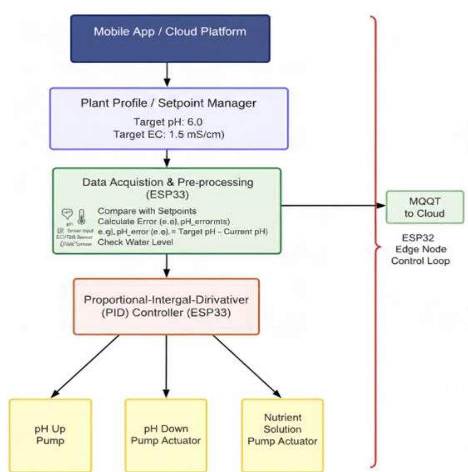


Fig 3. Detailed Control System Logic Flow Diagram for the ESP32 Edge Node

People can also build their own custom templates if the standard ones do not quite fit the situation. In that case, the setpoints turn into whatever values the user types in. The PID controller stays busy trying to reach those levels and hold them steady. It does this for as long as the system remains powered on. Right alongside that, the ESP32 pushes out the current system readings plus the target setpoints. It sends them over to the cloud server running on Node.js through MQTT. All the data ends up stored in the main database. That database sits in the cloud too, handled by MongoDB as the storage service.
Everyone needs to log into the app using their own credentials first. The server handles the check with JSON Web Token on the backend. This step makes sure the user is who they claim to be.

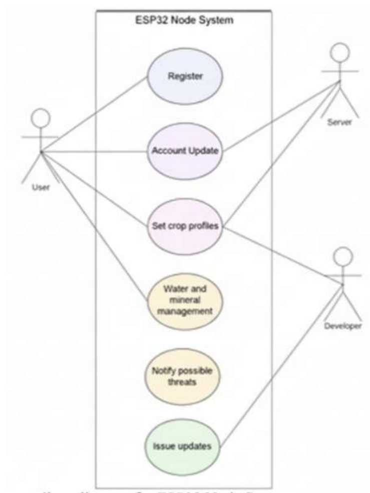
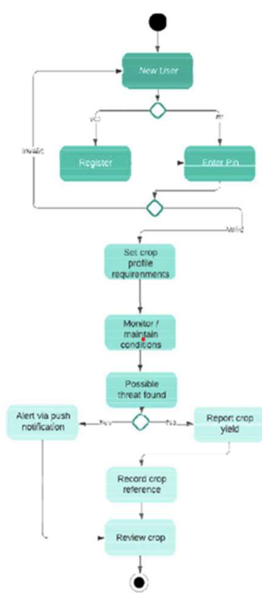


Figure 4. Use case diase diagram for ESP32 Node System

The ESP32 microcontroller sits at the center of everything in this project. It takes care of three main tasks pretty much all the time. One involves grabbing analog values from the sensors attached to it. The ESP32's ADC turns those into digital signals right away. Another task runs the full process control side of things. That covers selecting the plant profile template for setpoints, running the PID controller, and managing the actuator drivers. The third task sends those sensor values up to the cloud-based HTTPS server. It uses MQTT for the transfer. From there, the frontend mobile app can request the environmental parameters through API calls.



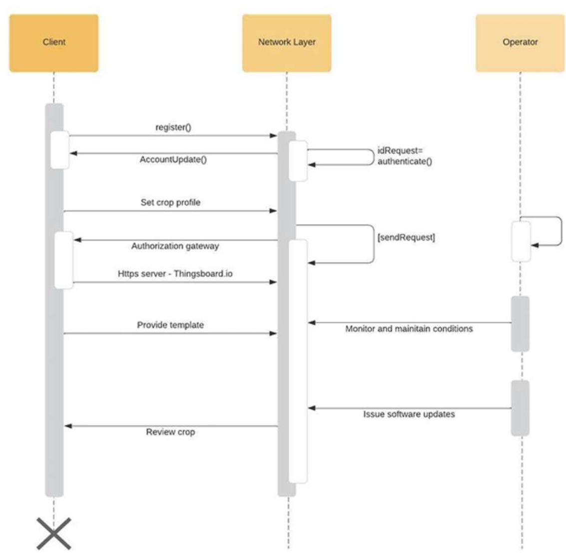


Fig 5. Activity diagram

Figure 6. Sequence diagram

V. Results and Discussion

In this project, we managed to grow a bunch of everyday vegetables. These included things like lettuce, spinach, fenugreek, beans, ladyfingers, and radish. The whole point of doing this was to get hands-on experience with their growth patterns. We wanted to understand their exact needs for food and how they handled different kinds of light. This was all in a setup using automated hydroponics, both natural and artificial lighting.

Our platform based on the ESP32 brought some clear benefits. One big one was space optimization for landscape management. The system works well in tight spots. It delivers everything plants need just right. Hydroponics makes it efficient too. So you can pack in a lot of plants. This fits perfect for city living, like on apartments or balconies.

Another advantage was saving a ton of water. The closed-loop design in our hydroponic setup is really good at that. Early checks show it uses only about five percent of the water that old-school irrigation does. That makes it great for the environment and saves money too.

We also got precise control over the environment, especially temperature. The ESP32 automation lets growers tweak the small details of the air around the plants. This means setting exact levels for heat, moisture, and light schedules. It is similar to what you see in high-end greenhouses. Farmers can fine-tune everything for the best plant health. In the end, that boosts their profits.

Nutrient use was optimized in a smart way, making fertilizers go further. The automated setup controls how nutrients get delivered completely. Users figure out what each plant type needs at different stages before starting. Then the ESP32 runs peristaltic pumps to add them precisely to the water. There is no waste or changes like you might get in dirt growing. Everything stays in the reservoir.

Pests and diseases dropped a lot too. Without soil, the system avoids problems from the ground, like worms, rodents, or even birds. Fungal issues such as Fusarium, Pythium, and Rhizoctonia are less likely. Good nutrient handling makes plants stronger overall. They resist threats better naturally.

To test how well the system worked, we zeroed in on growing spinach. The setup for this part had a special tray. It held 15 spots for plants, laid out in five rows. We put 10 to 15 seeds in each spot at first. That way, we got good germination. In the end, one strong plant filled each space.

After about 13 to 19 days as seedlings, we moved the spinach to a bigger system. This one had 18 stages for hydroponics. It kept the growth going smoothly. The setup supported ongoing cycles without stopping. In general, the full cycle for leafy greens like spinach went from seeds to harvest in around 30 days. This was steady in our automated system.

VI. Conclusion

Industrialization caused a real shortage of land for farming. That pushed things toward hydroponics, which really started a fresh chapter in how we grow crops. Our study showed that an IoT-based hydroponic setup gives better yields compared to traditional soil farming. This project works as a solid monitoring tool for city growers. It sticks to hydroponics basics, meaning growing plants without any dirt at all. That approach helps a lot in tight spaces or bad weather spots. The main point here is to let indoor farming fans and those young plant lovers get live updates on their setup right from a phone app. We aimed to cut down startup costs by picking cheap sensors and basic single-board computers. Network use and power draw stayed front and center when we selected the data protocol.

The system lets users handle full control from start to finish. For instance, an emergency stop can halt the whole hydroponic operation if something goes wrong. Looking ahead, we plan to focus on spotting faults and sending error alerts. Without that, the idea stays pretty basic. The next steps include using simple rules for error reports to help users track down why a crop might fail. Early on, how data comes together relies on how well the system adapts and works in practice. Setup expenses drop when you go with affordable sensors, simple processors, and basic modules for sending info.

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