Journal Européen des Systèmes Automatisés
Vol. 57, No. 5, October, 2024, pp. 1273-1283
Journal homepage: http://iieta.org/journals/jesa

Automated IoT Solutions for Efficient Hydroponic Farming: Nutrients, PH and Lighting Management

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https://doi.org/10.18280/jesa.570503

Received: 22 May 2024
Revised: 29 September 2024
Accepted: 10 October 2024
Available online: 28 October 2024

Keywords:
hydroponics, soil less farming, raspberry Pi, IoT, automation, smart nutrition management

ABSTRACT

Hydroponics, a soil-less agriculture system, consumes less water and resources compared to traditional soil-based farming. However, it requires simultaneous monitoring of various parameters, making it challenging. This article explores a ground-breaking hydroponic system designed to revolutionize modern farming by creating a precision-controlled environment for plant growth. Our research developed a Smart Hydroponic farm using Internet of Things (IoT) technology to highlight its advantages over traditional human-intervened hydroponics. Given the high costs of organic farming, this paper offers a more feasible solution through automated hydroponics with remote monitoring and control. The system exemplifies smart agriculture by utilizing real-time sensors for light, pH, EC, temperature, water level, and a camera module, all managed by a Raspberry Pi processor. It aims to save labor and resources while providing precise control over watering and fertilization. The primary function of this hydroponic system is to automate parameter monitoring and control via actuators, facilitating faster production of green leafy vegetables and eliminating the labor-intensive tasks typically associated with farming.

1. INTRODUCTION

Hydroponics, a method of growing plants without soil, uses nutrient-rich solutions to foster plant growth, offering a transformative approach to agriculture. This method allows plants to grow 25-30% faster by directly exposing roots to nutrients and regulating atmospheric conditions. Traditional farming, reliant on extensive land use and fertilizers, degrades soil quality and leaves farmers vulnerable to environmental uncertainties. Hydroponics, particularly suited for urban areas with high vegetable demand, enables precise control of environmental parameters, benefiting both large-scale cultivators and urban gardeners. Integrating Internet of Things (IoT) technology into hydroponic systems revolutionizes traditional growing practices. Real-time sensors monitor pH levels, temperature, humidity, and nutrient concentrations, allowing automated adjustments to optimize conditions for plant health. Various hydroponic systems, from wick systems to aeroponics, offer versatile cultivation methods.

However, managing the environment in a greenhouse manually for hydroponic farming presents several challenges:

1. Temperature Control: Maintaining optimal temperatures is crucial, but fluctuations can occur due to external weather conditions, making consistent control difficult.

2. Humidity Regulation: High humidity can lead to mold and plant diseases, while low humidity may cause plant stress, requiring constant monitoring.

3. Light Management: Providing sufficient and controlled light, especially in regions with varying sunlight, often necessitates artificial lighting systems, which can be expensive and complex to manage.

4. Ventilation: Proper air circulation is essential to prevent the buildup of excess heat, humidity, or carbon dioxide, yet achieving uniform airflow can be challenging.

5. Water Quality: Ensuring consistent water quality and managing pH, nutrient concentrations, and salinity are vital to prevent plant stress or nutrient lockout.

6. Nutrient Imbalance: Regular testing and adjustment of nutrient solutions are necessary, as imbalances can lead to poor plant health or reduced yields.

7. Pest Control: While greenhouses provide a barrier to pests, some still infiltrate, and managing them in a controlled environment requires careful planning and sometimes biological control.

8. Energy Costs: The need for lighting, heating, cooling, and water circulation systems can result in high energy consumption, driving up operational costs.

9. Disease Management: Disease can spread quickly in a hydroponic system, so early detection and isolation of affected plants are critical.

10. System Maintenance: The complexity of maintaining pumps, sensors, and automated systems requires regular upkeep and technical know-how to avoid breakdowns.

Smart hydroponics, enhanced by IoT and data analytics, ensures precise nutrient delivery, minimal resource use, and higher crop yields. Advances in energy-efficient lighting and sustainable practices make hydroponics a promising approach for future farming. Our project employs advanced technologies, including IoT, Raspberry Pi, diverse sensors, MongoDB for data management, and a web-based interface for remote monitoring. This system automates nutrient dosing and lighting control, providing farmers with real-time insights and control to optimize crop growth and resource efficiency. In this paper, we present an automated hydroponics system with remote monitoring and control to facilitate faster growth of leafy vegetables and eliminate the labor involved. The next section presents a comprehensive review of the related work in the area. Section 3 presents the proposed methodology. The experimental results are presented in Section 4 and the paper is concluded in Section 5.

2. LITERATURE REVIEW

This section provides a detailed analysis of existing methods. Jones Jr. [1] offers comprehensive insights into hydroponics in a complete guide for growing plants hydroponically, catering to beginners and seasoned enthusiasts. With clear instructions and extensive expertise, Jones delves into various hydroponic systems, covering essentials such as plant nutrition, nutrient solutions, and application factors. Patil et al. [2] outline an IoT-based approach for monitoring hydroponics systems in real time, tracking essential parameters such as nutrient concentration, pH, temperature, and oxygen levels. By integrating IoT devices and sensors, remote management of the hydroponics setup becomes feasible, addressing the critical need for precise system control. This solution enables growers to optimize nutrient delivery and system parameters continuously, enhancing plant growth efficiency while minimizing operational costs. Hati and Singh [3] introduce Pheno-Parenting, an AI-driven phenotyping system, utilizing deep learning to analyze plant traits in soilless farming. Using advanced ML techniques like CNNs and RF, it predicts traits efficiently, enhancing soilless farming operations. It underscores AI's potential to maximize productivity, reduce environmental impact, and promote sustainability in agriculture. The insights provided advanced understanding and capabilities in AI-driven phenotyping, with wide-ranging applications across agricultural sectors.

Chaiwongsai [4] introduces an automated management system for tropical hydroponic cultivation, controlling temperature, pH, nutrient concentration, and oxygen saturation. Employing advanced algorithms, the system optimizes plant growth conditions, boosting yields and cutting operational expenses. It underscores the significance of efficient control systems in maximizing productivity and profitability. The insights provided enhance understanding and capabilities in tropical hydroponic cultivation. Changmai et al. [5] introduce a comprehensive approach to automating agricultural robotic operations using Deep Reinforcement Learning (DRL). By employing DRL algorithms like Proximal Policy Optimization (PPO) and Deep Q-Network (DQN), robots can autonomously learn and execute complex tasks. It underscores DRL's potential in optimizing agricultural operations, enhancing yields, and reducing costs. The insights provided advanced understanding and capabilities in DRL for agricultural automation, with broad applications across sectors. The system integrates sensors and cameras to monitor and adapt to changing environmental conditions.

Tatas et al. [6] discuss IoT-enabled hydroponic systems' potential to enhance productivity, profitability, and sustainability in agriculture. It presents a comprehensive approach to automating robotic operations in agriculture using DRL algorithms. Through continuous monitoring with IoT sensors, robots can adapt to changing conditions, maximizing yields. The report emphasizes the integration of advanced technologies for optimizing aquaponic systems, benefiting researchers, growers, and various agricultural sectors. Gokul et al. [7] introduce a smart hydroponic system utilizing IoT technology for enhanced management. Advanced machine learning algorithms optimize system operations, boosting productivity and profitability. It showcases IoT's transformative potential in agriculture, with adaptive algorithms minimizing resource consumption. The integration of IoT, machine learning, and robotics offers valuable insights into aquaponic system optimization, benefiting researchers, growers, and agricultural sectors. Hardeep and Dunn [8] offer practical insights for growers on maintaining optimal levels of electrical conductivity and pH guide for hydroponics. It emphasizes the critical role of these parameters in system functionality and plant health. Detailed measurement techniques and their application are provided. The guide explores the correlation between conductivity, pH, and plant well-being. Overall, it's an invaluable resource for enhancing understanding and skills in hydroponics.

Priya et al. [9] introduce an AI-enabled hydroponics system tailored for holy basil cultivation, addressing challenges like water scarcity. It highlights the system's potential to revolutionize cultivation practices and improve resource efficiency. A novel control algorithm optimizes solar energy utilization for system performance enhancement. The study offers valuable insights into AI-driven hydroponics systems' impact on holy basil cultivation, benefiting researchers and growers. Overall, it's a valuable resource for advancing understanding and skills in optimizing holy basil cultivation systems. Dinesh et al. [10] review IoT-based smart farming applications and wireless sensor networks in agriculture. It addresses challenges in integrating technology with traditional farming, offering insights for growers. Additionally, it explores applications in packing and transport, serving as a valuable resource for agriculture and IoT enthusiasts.

Dahane et al. [11] present a low-cost, sustainable irrigation system for smallholder farmers, integrating smart, open-source technology with a Fog-IoT-Cloud platform. It compares auto-encoders and generative adversarial networks for anomaly detection in environmental data and predicts key factors like air temperature, humidity, and soil moisture using CNN/BiLSTM architecture to provide actionable recommendations. Kori et al. [12] present a hydroponics IoT system for remote monitoring and control, optimizing plant growth and water management. Utilizing various sensors for temperature, humidity, pH, and nutrient levels, data is transmitted via an IoT gateway to a cloud platform for real-time analysis. A user-friendly mobile app enables remote monitoring and control, catering to farmers and hobbyists. Results showcase enhanced crop yield and water efficiency compared to soil-based methods. Blancaflor et al. [13] introduce an IoT monitoring system for hydroponics, tracking vital factors like temperature, humidity, and light intensity using sensors, microcontrollers, and communication protocols. Real-time data aids informed decision-making. A machine learning model predicts plant growth, aiding cultivation strategies. Modular design enables scalability and customization. Experimental results show accurate monitoring and enhanced plant growth.

Dudwadkar et al. [14] propose an IoT-driven hydroponics system for remote monitoring and control of pH, temperature, and nutrient levels. Employing sensors, microcontrollers, and communication protocols, real-time data facilitates optimized plant growth interventions. Results show enhanced crop yields and reduced water consumption, promising sustainable agriculture. Remote monitoring allows swift responses to environmental changes, mitigating crop failure risks and enhancing efficiency. Safira et al. [15] propose an IoT-driven monitoring system for nanobubble-based hydroponics, enhancing crop yields and resource efficiency. Utilizing sensors, microcontrollers, and communication protocols, it tracks parameters like temperature, humidity, and pH. Demonstrated effectiveness includes improved crop growth and reduced water consumption, promoting sustainability. Real-time monitoring and alerts enable swift responses to environmental changes, minimizing crop failure risks and enhancing efficiency.

Shubham et al. [16] advocate IoT benefits in hydroponics: real-time monitoring, automated nutrient/water delivery, and remote control. Results show enhanced yields, resource efficiency, promoting sustainability. Real-time monitoring enables swift responses, reducing crop failure risks, and enhancing efficiency. Potential for commercial scaling underscores viability as a soil-based farming alternative. Harikrishna et al. [17] propose greenhouse automation with IoT for hydroponics, enhancing yields and resource efficiency. It monitors environmental parameters using sensors, microcontrollers, and communication protocols. The authors claim improved crop growth and reduced energy consumption, promoting sustainability. Real-time monitoring and control automate greenhouse functions, enhancing efficiency with minimal manual intervention. Perwiratama et al. [18] propose smart hydroponic farming with IoT for climate and nutrient management, enhancing yields and resource efficiency.

Sabrina et al. [19] introduce an interpretable AI-based smart agriculture system utilizing IoT data for environment monitoring and farmer alerts. Fuzzy logic enables customization for diverse conditions. Machine learning detects anomalies, ensuring system reliability [20]. Thorough research on maize cultivation factors validates interpretability and accuracy. Experimental results confirm precise action triggering aligned with crop needs. Khan et al. [21] propose a real-time plant health assessment system utilizing AWS DeepLens and transfer learning for disease classification. Scalable cloud deployment enhances accessibility and reduces hardware costs [22, 23]. Pre-trained model fine-tuning on a custom dataset achieves high accuracy. Early disease detection decreases chemical usage, and enhances yields, promoting sustainability.

3. PROPOSED METHODOLOGY

The proposed Smart Hydroponics Farming IoT System represents a significant advancement in modern agriculture, offering novelty in its integration of real-time monitoring, automation, and data-driven decision-making.

Novelty:

- IoT sensors continuously monitor critical environmental parameters like nutrient levels, temperature, humidity, pH, and oxygen saturation, allowing for precise system control.
- Automation eliminates manual interventions, with systems adjusting parameters in real-time, optimizing conditions for plant growth.
- The integration of AI and machine learning (ML) algorithms for predictive analysis and anomaly detection further enhances the system's intelligence, allowing early issue identification and corrective actions.

Significance:

- By ensuring precise and consistent environmental conditions, the system significantly boosts crop yields, reduces water and nutrient usage, and minimizes operational costs.
- The automation of nutrient delivery and climate control ensures that plants receive optimal care 24/7, increasing both productivity and efficiency.
- Remote management capabilities enable growers to monitor and control the system from any location, enhancing flexibility and minimizing labor.
- The use of AI in analyzing plant traits and optimizing resource usage promotes sustainability, reducing the environmental impact compared to traditional farming methods.
- Overall, this system supports scalable, efficient, and eco-friendly farming practices, positioning it as a transformative solution for the future of agriculture.

The detailed implementation analysis of Smart Hydroponic farming, which is developed by integrating the Raspberry Pi, IoT environment with web application is explained in this section. The objectives of the proposed smart hydroponic farming system are:

- System Development: Design an integrated automated system for hydroponic farming to control and optimize nutrition dosing, pH levels, and lighting conditions.
- Nutrition Optimization: Develop algorithms for precise nutrient dosing based on plant growth stages, enhancing nutrient intake and minimizing waste.
- pH Regulation: Implement a system to monitor and adjust pH levels automatically, maintaining optimal conditions for crops.
- Lighting Control: Create a lighting control system to manage light intensity, duration, and spectrum, mimicking natural sunlight for optimal plant growth and energy efficiency.
- Data Monitoring and Analytics: Use sensors and data logging to continuously monitor nutrient levels, pH, and lighting, enabling real-time adjustments and long-term analysis.
- Remote Access and Control: Provide a user-friendly interface for remote monitoring and adjustments, allowing farmers to manage the system from

anywhere.

Figure 1 illustrates the flow of information starting from sensor data collection, which is then transmitted to the backend API for processing and storage in the MongoDB database. The front-end dashboard enables users to visualize and analyze the data collected from the sensors. In summary, the high-level diagram provides a holistic view of how the various components of the Smart Nutrition Management system collaborate to support effective monitoring and management of hydroponic farming practices. The BH-1750 sensor is used to read and measure ambient light intensity ranging from 0 to 65535 Lux (L). The BH-1750 Light sensor directly gives output in Lux. The sensor's spectral response function is approximately close to the human eye's. The DHT-11 sensor is used for parameters such as the temperature and humidity of the atmosphere. The DF-Robot pH sensor is used for extracting the PH levels such as the acidic and basic nature of the water. The DF-Robot EC sensor is used to extract the electrical conductivity of water additionally, camera modules capture the images of plants with the specified time scale. Finally, the Raspberry Pi receives all sensor values and images and sends these data to the MongoDB Atlas database. Figure 2 shows the low-level representation of how Raspberry is connected to various external devices like DC-motor pumps, grow lights, and sensors. Figure 3 shows the high-level view of the software system.

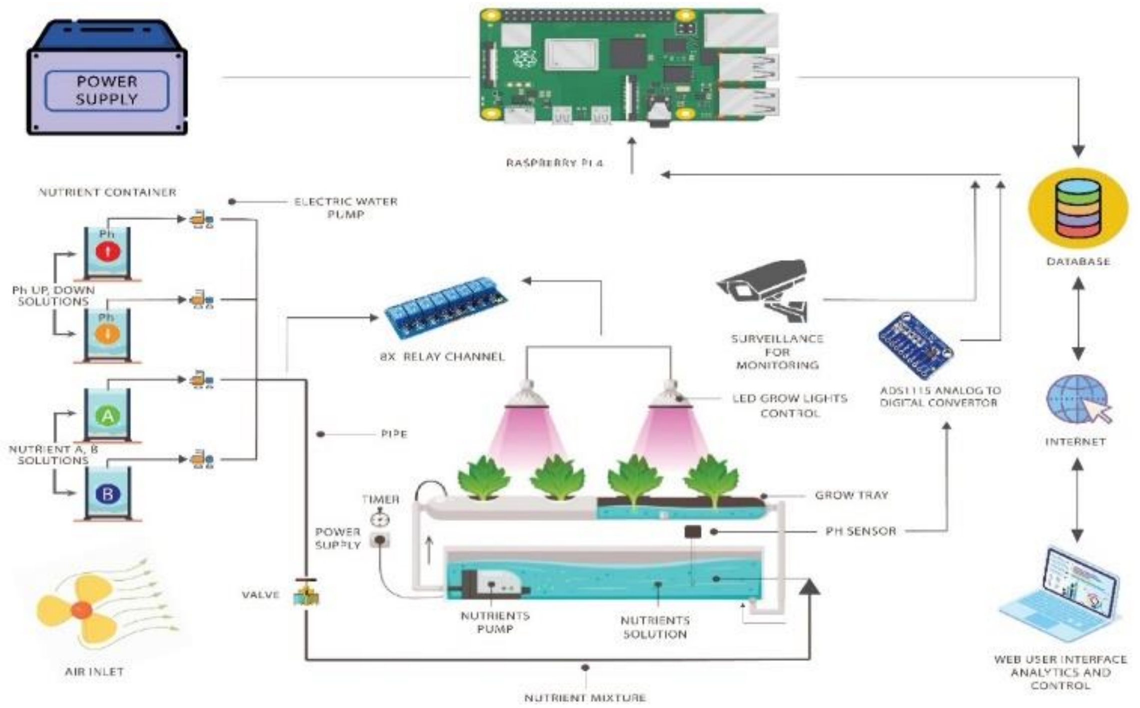

Figure 1. Architecture of smart hydroponic farming IoT system

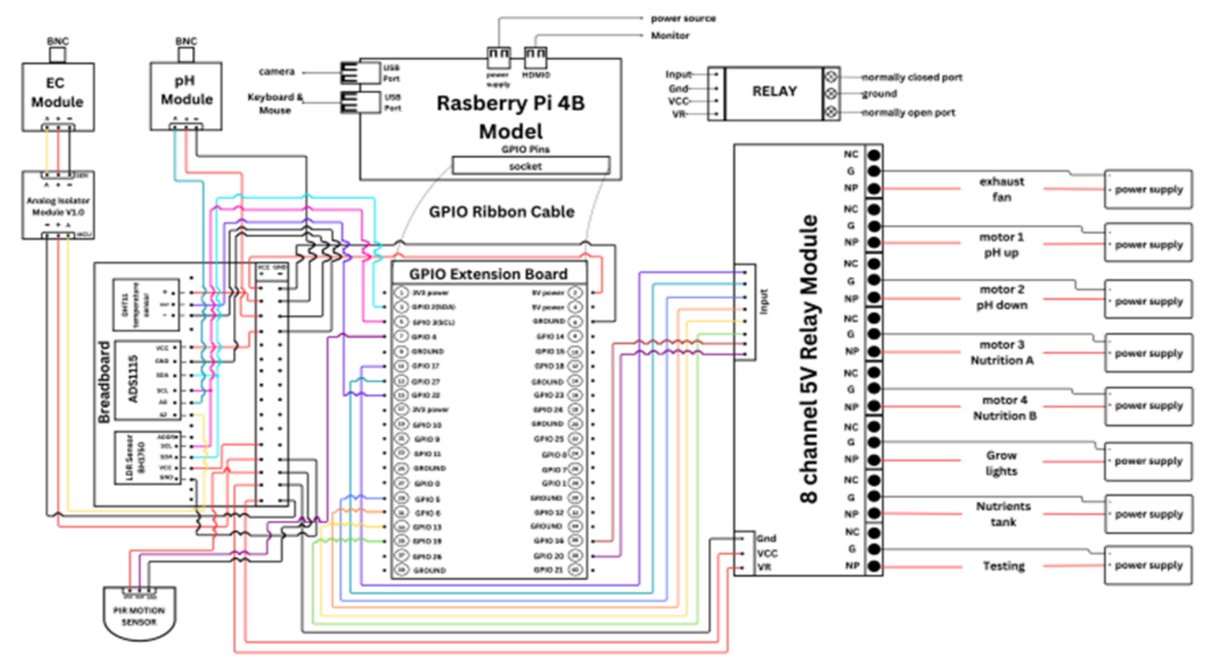

Figure 2. Circuit diagram

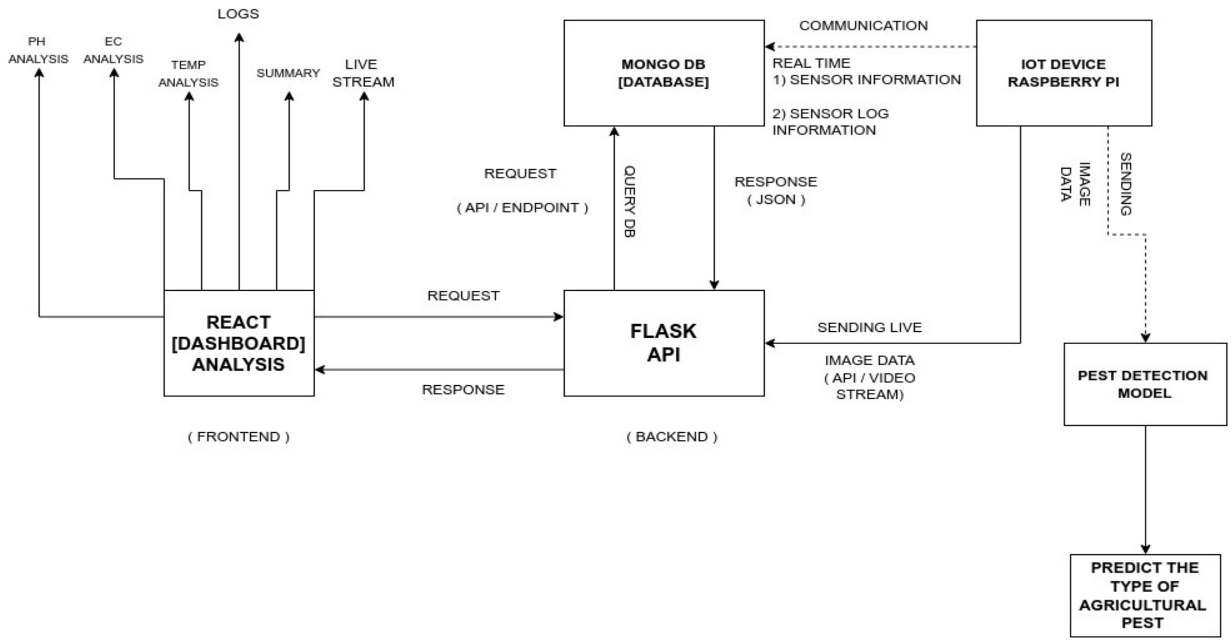

Figure 3. Software architecture

3.1 System calibration and validation

The calibration and validation process of the proposed IoT-based Smart Hydroponic Farm Management System described involves several key steps to ensure accurate data collection and system functionality.

Calibration Process:

- **Sensor Calibration**: Each sensor used in the system (BH-1750 for light intensity, DHT-11 for temperature and humidity, DF-Robot pH, and EC sensors) needs to be calibrated to ensure that the measurements accurately reflect real-world conditions.
  - **BH-1750 Light Sensor**: This sensor, measuring ambient light in Lux, should be calibrated by comparing its readings to a standardized light meter under controlled conditions to account for variations in sensor sensitivity.
  - **DHT-11 Temperature and Humidity Sensor**: The temperature and humidity readings are compared against trusted thermometers and hygrometers. Calibration adjustments are made to correct any deviations.
  - **DF-Robot pH Sensor**: The pH sensor is calibrated using buffer solutions of known pH (e.g., pH 4, 7, and 10). Adjustments are made to align the sensor's readings with these standards.
  - **DF-Robot EC Sensor**: This sensor measures the electrical conductivity (EC) of water, indicating nutrient concentration. It is calibrated using solutions with known conductivity levels to ensure precise nutrient monitoring.
- **Camera Calibration**: The camera capturing images of plants must be calibrated for optimal image quality in varying light conditions. Adjustments in focus, white balance, and resolution settings ensure that the images are clear for analysis.
- **System Integration Calibration**: Once individual sensors are calibrated, the entire system (sensors, Raspberry Pi, database, and API) must be tested to ensure that the data flow from sensors to the MongoDB database and visualization dashboard is functioning properly. Any discrepancies between the actual sensor readings and the data displayed on the front-end need to be adjusted.

Validation Process:

- **Field Testing**: The calibrated system is deployed in a controlled environment where sensor readings are cross validated with independent tools or reference devices. For instance, the system's pH, EC, temperature, humidity, and light intensity readings are compared to manual measurements to verify their accuracy.
- **Real-Time Monitoring**: During validation, real-time sensor data collected by the Raspberry Pi is continuously compared to expected environmental conditions. This ensures that the system responds accurately to changes in temperature, pH, light, and nutrient levels.
- **Backend Validation**: The data processed by the backend API and stored in the MongoDB database is validated by comparing it with the raw sensor data collected. This checks for any discrepancies in data transmission, processing, or storage.
- **User Interface Validation**: The front-end dashboard, which visualizes sensor data, is validated by comparing the displayed data with the backend data to ensure accurate representation of real-time conditions.
- **Automated System Testing**: The connection of the Raspberry Pi to external devices such as pumps and grow lights is validated through automated tests, ensuring that the actuators respond correctly based on the sensor readings. For instance, if the light intensity

falls below a certain threshold, the system should automatically trigger the grow lights, and this response is validated during testing.

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Final Validation

- The system undergoes a final validation process where its performance is tested over a prolonged period to monitor stability, responsiveness, and accuracy. Any anomalies or deviations from expected behavior are analyzed and corrected before full deployment.

This combination of calibration and validation ensures system operates reliably, providing accurate data to optimize plant growth conditions and farm management practices.

3.2 Algorithms and control strategy

In the proposed system, various algorithms and control strategies are employed for precise nutrient dosing, pH regulation, and lighting control. These strategies leverage real-time sensor data and automation to optimize crop growth in hydroponics. Here's a detailed discussion of these control mechanisms:

Nutrient Dosing Control

The Proportional-Integral-Derivative (PID) control algorithm is used to regulate nutrient levels in hydroponic systems. This algorithm adjusts the dosing of nutrients based on the difference between the measured electrical conductivity (EC) and the desired setpoint. The controller measures the deviation between the current EC level and the target value, adjusting nutrient dosing proportionally to this error. The system continuously monitors the EC sensor readings and adjusts the nutrient solution accordingly. When the EC falls below the desired level (indicating nutrient depletion), the system triggers the nutrient pumps to release the appropriate amount of nutrients. The dosing is fine-tuned to maintain optimal nutrient levels without oversaturating the water, which could harm plant health.

pH Control

The system uses pH sensor feedback to constantly monitor water acidity and bases its control actions on fuzzy logic to smooth out any abrupt pH fluctuations. This is crucial for preventing sudden pH shifts that could damage plants or lead to nutrient lockout.

Lighting Control

Lighting is managed using light intensity feedback with PID Control. The BH-1750 sensor measures ambient light intensity in real-time, providing input for controlling artificial lighting to maintain consistent light exposure for crops. Similar to nutrient dosing, a PID controller adjusts the lighting based on the deviation from the desired light intensity levels. If the ambient light is insufficient (e.g., during cloudy days or at night), the artificial grow lights are powered on proportionally to the deficit. The system dynamically adjusts grow lights based on real-time sensor readings, ensuring that crops receive a consistent amount of light throughout the day. The combination of natural sunlight and artificial grow lights helps maximize photosynthesis and plant growth efficiency while minimizing energy use by turning off lights when sufficient sunlight is available.

Temperature Control

Temperature control is a critical aspect of ensuring optimal growing conditions for crops. Temperature regulation is performed by combination of PID control leveraging real-time sensor feedback to maintain stable temperatures. Proportional-Integral-Derivative (PID) Control is employed to regulate temperature by maintaining the setpoint temperature range, which is ideal for the specific crops being grown. The desired temperature is defined based on the crop requirements, typically between 18°C and 30°C for many hydroponic plants. The system calculates the difference (error) between the current temperature (measured by the sensor) and the desired setpoint temperature. If the temperature is too low or too high, the proportional component adjusts heating or cooling accordingly. For example, if the temperature is higher than the setpoint, water chillers or ventilating fans are turned on or adjusted to bring the temperature closer to the target.

4. RESULTS AND DISCUSSIONS

IoT technology in automated hydroponics highlights several significant benefits that contribute to enhanced accuracy, efficiency, and environmental sustainability. These advantages stem from the integration of sensors, real-time data processing, automation, and advanced control strategies, which enable precise and efficient management of critical environmental factors such as nutrient dosing, pH levels, lighting, and temperature. The summary of the key benefits, along with areas where the proposed system is as follows:

Enhanced Accuracy

- **Precision in Nutrient Delivery**: The IoT-enabled system continuously monitors nutrient concentrations using electrical conductivity (EC) sensors and automatically adjusts nutrient dosing with precision. This minimizes nutrient wastage, prevents deficiencies or excesses, and supports optimal plant growth.

- **Accurate pH Control**: By employing real-time pH sensors and fuzzy logic control, the system maintains pH within the ideal range, preventing nutrient lockout and ensuring healthy plant development.
- **Optimized Temperature and Lighting**: The system adjusts temperature and artificial lighting based on real-time ambient temperature and light intensity data, ensuring that crops are maintained at optimal temperature and receive the exact amount of light needed for photosynthesis. This level of precision boosts growth rates while reducing energy consumption.

Increased Efficiency

- **Automation of Key Processes**: IoT technology automates critical farming processes like nutrient dosing, pH regulation, and environmental control (lighting, temperature and humidity). This reduces the need for manual intervention and optimizes system performance, leading to more consistent and reliable crop yields.
- **Time and Resource Savings**: Automation cuts down on labor requirements, allowing growers to focus on higher-level tasks rather than constant monitoring and manual adjustments. Additionally, by efficiently controlling resource usage (water, nutrients, and electricity), the system lowers operational costs.
- **Data-driven decision-making**: Real-time data collected by IoT sensors is continuously processed and stored, allowing growers to make informed decisions based on historical and current trends. This data also feeds into predictive models that enhance system efficiency over time.

Environmental Friendliness

- **Reduced Resource Consumption**: The IoT-based system is designed to optimize resource usage, reducing water consumption and nutrient wastage through precise control mechanisms. This minimizes the environmental footprint compared to traditional soil-based farming methods.
- **Sustainable Energy Use**: By integrating smart lighting control (e.g., using LED grow lights based on real-time light intensity data), the system reduces energy consumption, especially during periods when natural sunlight is sufficient. AI-driven predictive can controls further improve energy efficiency by adjusting heating and cooling preemptively.

Remote Monitoring and Control

- **Convenient Access to Data**: The system enables remote monitoring and control through website, mobile apps and dashboards, giving growers the flexibility to manage their farms from anywhere. This reduces downtime, as any issues with pH, temperature, or nutrient levels can be addressed swiftly.
- **Minimized Risk of Crop Failure:** With continuous real-time monitoring, IoT systems can alert farmers to any deviations from optimal conditions. This allows for quick corrective actions, reducing the risk of crop failure due to unexpected environmental changes or equipment malfunctions.

While the benefits of IoT technology in hydroponics are clear, the specific improvements the proposed system achieves compared to other solutions:

1. **Superior Accuracy and Control**: The system could be benchmarked against existing hydroponic solutions to show how its IoT and Control Strategies provides finer control over nutrient and pH levels. A comparison of how precise dosing or pH regulation impacts plant health and yield could further strengthen the argument.
2. **Enhanced Efficiency**: Existing systems rely on simple reactive control mechanisms. The proposed system highlighted as a differentiator, explaining how it optimizes resource use ahead of environmental changes (e.g., reducing energy costs by predicting temperature changes and adjusting heating/cooling systems preemptively).
3. **Cost Reduction**: The system minimized operational costs by optimizing resources more effectively than existing solutions. For example, water, energy, or nutrient savings achieved through the control algorithms.

The web portal provides a user-friendly interface for monitoring and managing hydroponic systems. Upon logging in with credentials, users are directed to a general dashboard showcasing real-time data including EC value, pH value, humidity, temperature, and light intensity. A dynamic line graph illustrates EC and pH trends over time. Dedicated pages for EC and pH monitoring offer detailed line graphs and tables displaying logged values over time. Additionally, a separate page is allocated for temperature monitoring, featuring a similar format of line graphs and tables for tracking temperature fluctuations. Furthermore, a summary page consolidates data for all parameters, offering a comprehensive overview of logged information. Additionally, the website features a log page documenting the activation and deactivation of instruments during regulation processes. This log provides valuable insights into system operations and changes over time. Overall, the website offers extensive monitoring and logging capabilities, facilitating efficient management of hydroponic systems. Also, the website is deployed at Smart-Hydro where the farmer can witness the values from anywhere.

Figure 4 presents the web dashboard interface, offering a comprehensive overview of critical environmental parameters vital for hydroponics farming. Parameters like light intensity, pH levels, electrical conductivity (EC), and temperature are prominently displayed, providing real-time updates. The dynamic graph showcases fluctuations in pH and EC levels, ensuring users are informed of changes every 15 minutes as new sensor data is received. This intuitive platform facilitates informed decision-making, allowing farmers to optimize crop growth by closely monitoring and analyzing environmental conditions. Moreover, users can customize alert settings and access historical data logs for retrospective analysis.

Figure 5 presents the web page showing a dynamic graph showcasing real-time variations in electrical conductivity (EC) values over time, updating instantly as new sensor data is received. Time intervals are represented along the x-axis, while EC levels are indicated on the y-axis. Concurrently, a detailed table complements the graph, providing a comprehensive breakdown of EC values corresponding to specific time points. This interactive display empowers users to closely monitor EC fluctuations, facilitating informed decisions in managing hydroponic systems. With continual data updates, users can effectively track EC dynamics, ensuring optimal nutrient levels for crop growth, while maintaining originality.

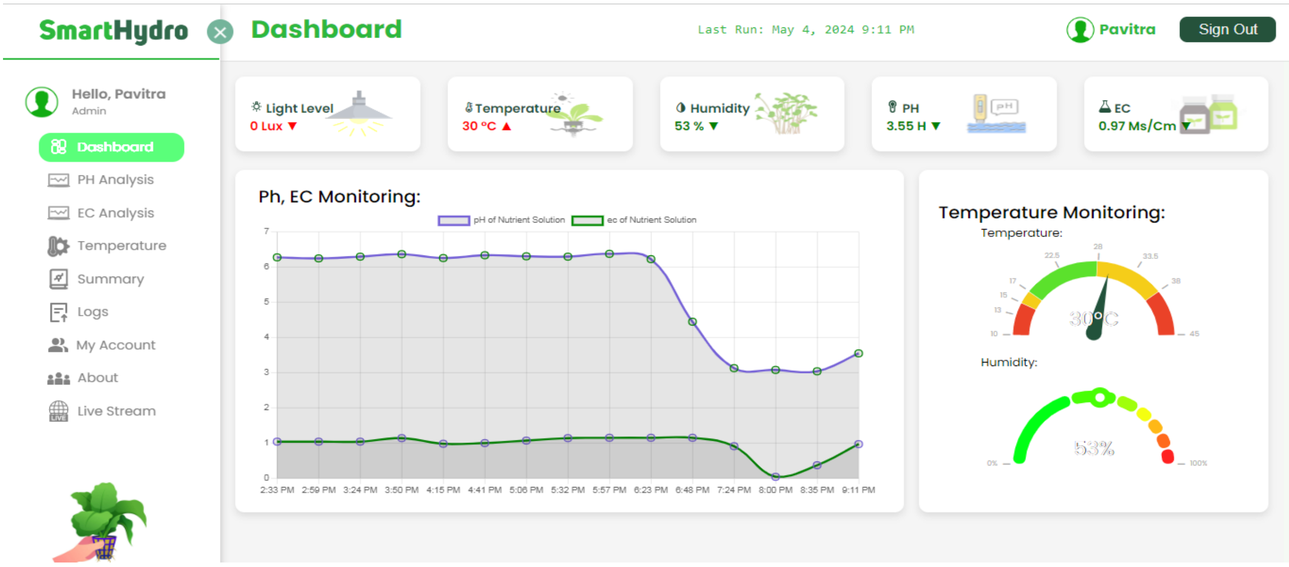

Figure 4. Software architecture

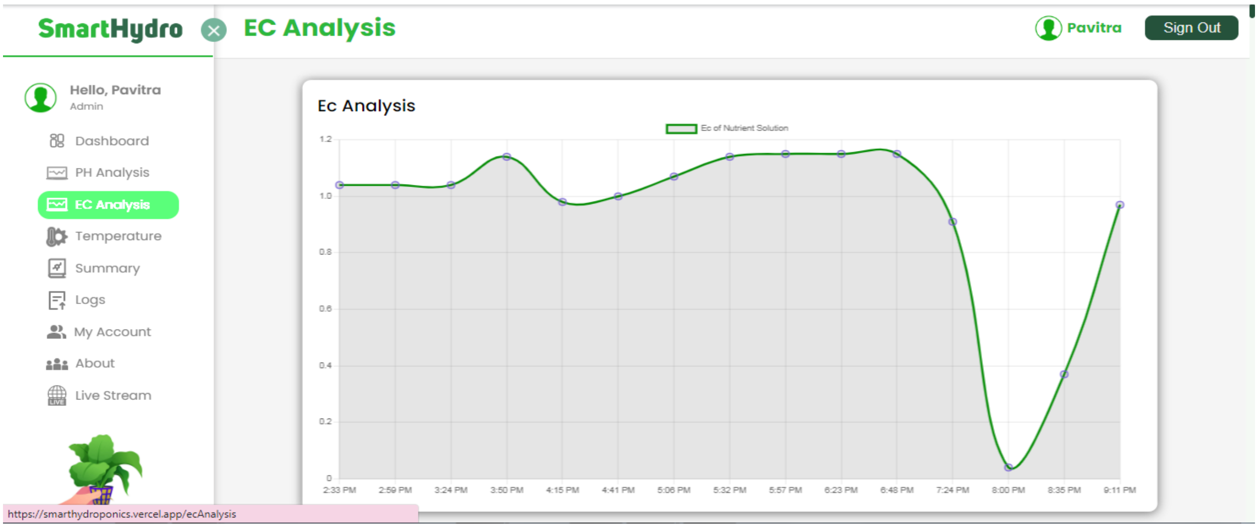

Figure 5. EC analysis

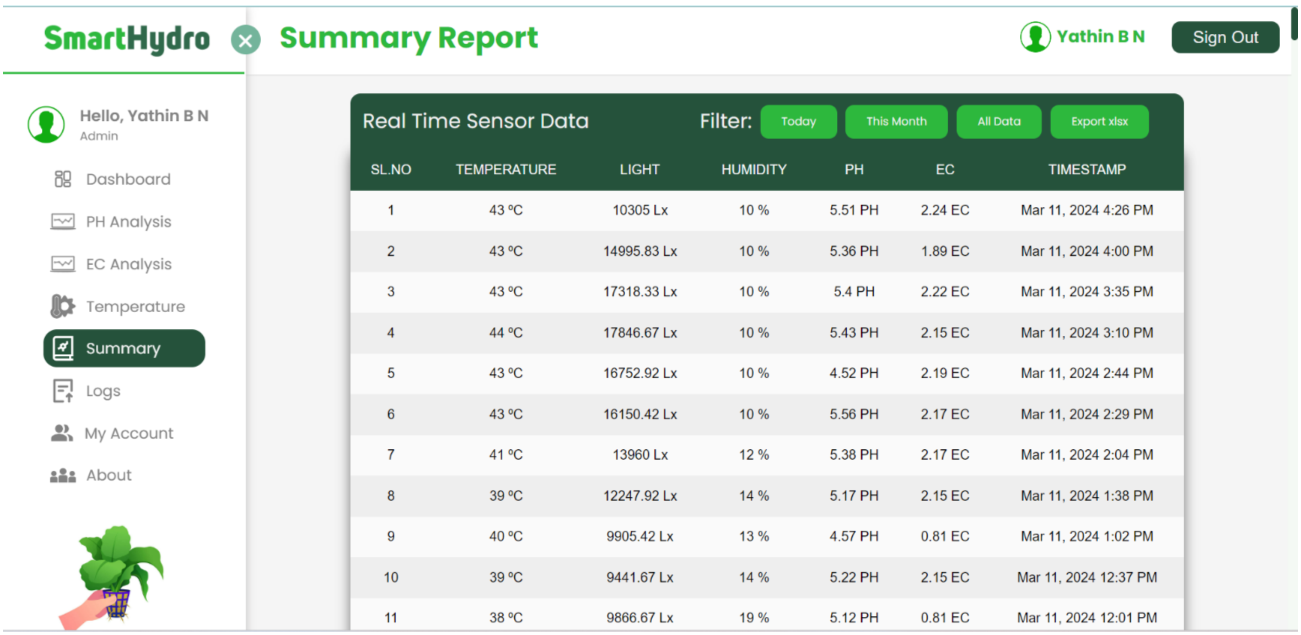

Figure 6. Summary report

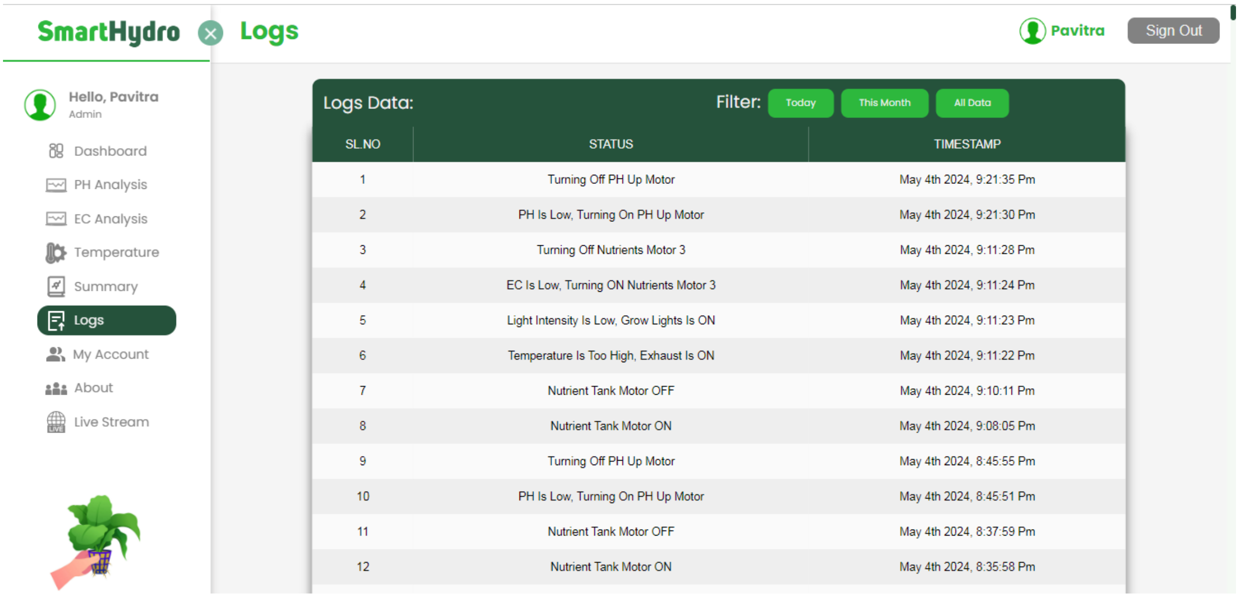

Figure 7. Logs

Figure 8. Live setup

Figure 6 presents a comprehensive table showcasing real-time values of all environmental parameters pertinent to the hydroponics system. Figure 7 features a dynamic interface illustrating the operation of five tanks within the hydroponics system. These tanks include the nutrition tank, responsible for pumping optimized EC and pH conditions into the system, as well as separate tanks for pH adjustment (pH up and pH down), nutrition, and water storage. Additionally, there are motors assigned to regulate the EC and pH levels in the system, along with growth lights and an exhaust fan for environmental control. The webpage logs the operational status of each component, indicating which instruments are currently running and when they have stopped. This information is updated in real-time, providing users with immediate insights into the system's functionality. The logging feature ensures transparency and allows users to track the performance of individual components over time, aiding in troubleshooting and maintenance efforts. This functionality enhances the usability of the webpage, empowering users to efficiently monitor and manage the hydroponics system.

Figure 8 illustrates the live stream webpage that offers users a captivating real-time view of the hydroponic plants within the system. Through a high-definition camera setup, users can observe the growth and development of the plants as it happens, providing an immersive experience into the hydroponic environment. This live stream feature allows users to remotely monitor their plants from anywhere with internet access, enabling them to stay connected and always engaged with their cultivation efforts. With its seamless integration and user-friendly interface, the live stream webpage enhances the accessibility and appeal of hydroponic farming, fostering a deeper understanding and appreciation for this innovative agricultural practice.

5. CONCLUSION

The integration of IoT technology into automated hydroponics represents a significant advancement in agriculture, offering improved accuracy, efficiency, and sustainability. By enabling real-time monitoring and control of key environmental factors like temperature, humidity, nutrients, and lighting, the system ensures optimal plant growth conditions. The seamless interaction of sensors, actuators, and control algorithms allows for precise management, while IoT platforms offer remote access, allowing farmers to monitor and control their systems from any location. This data-driven approach supports continuous optimization, leading to resource-efficient farming with reduced wastage of water, energy, and nutrients. The system ultimately promotes higher productivity and resilience, contributing to food security in an unpredictable global environment.

Despite these advantages, the study has limitations, including the need for more detailed experimental validation to quantify its performance improvements in multi-crop growing scenario, scalability concerns for larger farms, and the potential cost burden for smallholders. Future research could focus on improving predictive algorithms for more complex environmental changes, designing systems that can scale more effectively, and making the technology more affordable. Integrating renewable energy sources could also enhance sustainability. Overall, IoT-based automation in hydroponics is a promising step towards more efficient and sustainable farming, with further research poised to unlock its full potential.

ACKNOWLEDGEMENT

This research was funded by Vision Group on Science and Technology (VGST), Karnataka Science and Technology Promotion Society (KSTePS), Department of Science and Technology, Government of Karnataka for their invaluable financial support, under VGST Grant Scheme: RGS-F/GRD No. 1081, letter No: KSTePS/VGST/2021-22/RGS-F/GRD-1081/159/2022-23/69, which made this research possible. We extend our sincere thanks to the Management, Principal, HOD, Research Dean and Chief coordinator, SJB Institute of Technology, Bangalore, Karnataka, for providing us constant support throughout the period of our research work.

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