A Low-Complexity IoT Framework for Real-Time Monitoring in Hydroponic Systems

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Abstract. In hydroponic cultivation, maintaining proper nutrient concentration and environmental conditions is essential for healthy plant growth. Continuous monitoring of these parameters is therefore an important requirement in hydroponic systems. Although several IoT-based solutions have been proposed for hydroponic monitoring, many existing approaches depend on complex wireless communication methods or expensive sensing devices, which are not suitable for small-scale or low-cost setups. In this work, a simple and low-cost IoT-based hydroponic monitoring system is presented. The system focuses on efficient acquisition of real-time data using a serial communication approach along with web-based visualization. Key parameters such as nitrogen, phosphorus, potassium, temperature, and humidity are monitored continuously. Experiments conducted in a controlled hydroponic setup show that the monitored parameters exhibit stable behavior over time, indicating reliable system performance. The proposed system demonstrates that effective real-time monitoring in hydroponic environments can be achieved using a simpler and more affordable system architecture.

Keywords: Hydroponics, IoT-Based Monitoring, Nutrient Solution Analysis, Environmental Monitoring, Smart Agriculture

1 INTRODUCTION

Hydroponic cultivation is increasingly being adopted as an alternative method for growing plants, particularly in regions where land availability or soil quality is a concern. By delivering nutrients directly through water, hydroponic systems allow better control over plant growth while making efficient use of available resources. However, the performance of such systems depends

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strongly on how consistently the nutrient and environmental conditions are maintained.

In a typical hydroponic setup, parameters such as nutrient composition, temperature, and humidity play an important role in plant development. Nutrients including nitrogen, phosphorus, and potassium must be supplied in appropriate proportions, as variations in these values can affect plant health and growth. Environmental conditions also influence nutrient absorption and overall system stability. For this reason, continuous monitoring of both nutrient and environmental parameters is necessary to ensure smooth operation of hydroponic systems.

With the growth of Internet of Things technologies, several monitoring solutions have been proposed for hydroponic and controlled-environment applications. Many of these systems rely on wireless communication and advanced sensing platforms to provide remote monitoring and automation. While effective, such approaches often increase system complexity and cost, which can be a limitation for small-scale or budget-conscious hydroponic installations.

To address these issues, this work presents a simple and low-cost IoT-based monitoring system designed specifically for hydroponic applications. The proposed system avoids complex wireless communication and instead uses serial-based data acquisition to collect sensor readings and display them through a web-based interface. The system continuously monitors key nutrient parameters such as nitrogen, phosphorus, and potassium, along with temperature and humidity, enabling users to observe changes in real time and take appropriate action when required. Experimental validation carried out under controlled hydroponic conditions demonstrates stable parameter behavior over time, indicating reliable system performance.

The remainder of this paper is organized as follows. Section II reviews related work on IoT-based hydroponic monitoring systems. Section III describes the proposed system architecture and methodology. Section IV presents the experimental setup and discusses the results obtained. Finally, Section V concludes the paper and outlines possible directions for future work.

2 RELATED WORK

Recent studies have explored the use of Internet of Things technologies for monitoring and managing hydroponic systems. By integrating sensors with microcontrollers and communication modules, these systems enable real-time observation of nutrient and environmental parameters, thereby improving control over plant growth conditions [1–3]. Several works have reported web-based and mobile-based interfaces that allow users to remotely monitor hydroponic setups, highlighting the potential of IoT in controlled-environment agriculture.

Many of the existing IoT-based hydroponic monitoring systems employ wireless communication technologies such as Wi-Fi, ZigBee, or LoRa to transmit sensor data to cloud platforms or remote servers [4–6]. While these approaches offer flexibility and remote accessibility, they often increase system complexity and cost. In addition, wireless communication introduces challenges related to power consumption, network reliability, and maintenance, which can affect long-term deployment, especially in small-scale installations.
Some researchers have also focused on automated control of hydroponic systems using advanced sensing and communication architectures. Although these systems demonstrate improved precision and automation, they typically rely on expensive hardware components or complex system designs. As a result, their adoption in cost-sensitive or educational hydroponic setups remains limited.
In contrast to these approaches, the present work focuses on developing a simple and cost-effective hydroponic monitoring system that emphasizes system-level simplicity and reliable real-time data acquisition. By using a serial-based communication approach combined with web-based visualization, the proposed system aims to reduce architectural complexity while maintaining continuous monitoring of essential hydroponic parameters.

3 SYSTEM ARCHITECTURE

The flowchart of the proposed system is shown in Fig. 1.

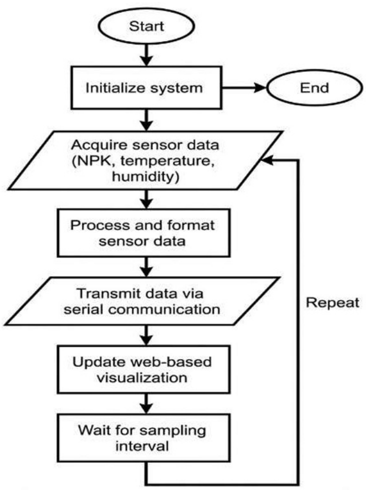

Fig. 1. System Architecture

The working flow of the proposed IoT-based hydroponic monitoring system follows a simple and continuous cycle, as shown in the flowchart. At the beginning of operation, the system initializes the microcontroller along with all connected sensors to ensure stable data collection. Once initialization is complete, the system periodically reads nutrient and environmental parameters from the hydroponic setup, including nitrogen, phosphorus, potassium, temperature, and humidity. These parameters are selected because they play a direct role in nutrient availability and plant growth in hydroponic cultivation.

After acquisition, the sensor readings are processed and organized into a structured format suitable for transmission. Instead of relying on complex wireless communication, the proposed system uses a serial-based data transfer approach, which reduces communication overhead and improves reliability for small-scale hydroponic installations. This design choice highlights the system-level simplicity of the proposed architecture while still supporting real-time monitoring.

The processed data received at the processing unit are then used to update a web-based visualization interface, allowing users to observe system conditions as they evolve over time. By presenting the information in real time, the system enables timely identification of variations in nutrient concentration or environmental conditions. Following each update, the system waits for a predefined sampling interval before repeating the monitoring cycle. This continuous operation ensures consistent data availability while maintaining a simple, low-cost, and efficient monitoring framework tailored for hydroponic applications.

4 EXPERIMENTAL SETUP

The overall architecture of the proposed system can be represented as shown in Fig. 2. The proposed system will be used for monitoring various environmental and nutrient parameters that can be used for efficient irrigation. The proposed system will utilize multiple sensors to monitor various parameters like nutrient concentration, environmental conditions, and water level. The proposed system will utilize a microcontroller unit to communicate the sensor values to a serial communication interface. The values will be sent to a data processing system for further processing. Finally, the processed values will be represented in the form of a web-based visualization system.

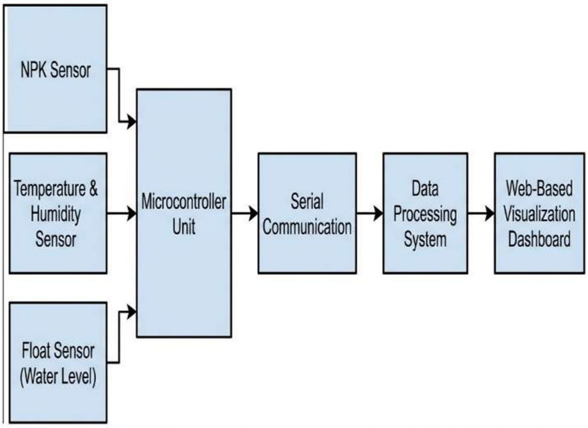

Fig. 2. Block Diagram

The experimental evaluation of the proposed IoT-based hydroponic monitoring system was carried out using a laboratory-scale hydroponic setup under controlled indoor conditions. The objective of the experiment was to observe the behavior of nutrient, environmental, and water-level parameters during continuous system operation and to validate the reliability of the proposed monitoring architecture.

The hydroponic setup consisted of a nutrient solution reservoir in which sensors were placed to collect real-time data. An NPK sensor was used to monitor the concentration of nitrogen, phosphorus, and potassium in the nutrient solution. Environmental conditions around the setup were measured using a temperature and humidity sensor. In addition, a float sensor was installed in the nutrient reservoir to monitor the water level and ensure consistent solution availability during the experiment. All sensors were interfaced with a microcontroller that served as the central data acquisition unit.

Sensor readings were sampled at fixed time intervals to enable continuous monitoring. The collected data were processed by the microcontroller and transmitted to a local processing system through serial communication. This communication approach was selected to provide stable and low-overhead data transfer without relying on wireless connectivity. At the processing system, the received data were organized and displayed using a web-based visualization interface, allowing real-time observation of system parameters.

The experiment was conducted for a predefined duration under steady operating conditions to analyze parameter trends over time. During this period, nutrient concentration, environmental conditions, and water level were continuously recorded without manual intervention. The acquired data were later used for time-series analysis to evaluate system performance and monitoring stability.

5 RESULTS AND DISCUSSIONS

This section presents the experimental results obtained from the proposed hydroponic monitoring system. The performance of the system is evaluated by analyzing the temporal variation of nutrient parameters, environmental conditions, and water level under controlled operating conditions.

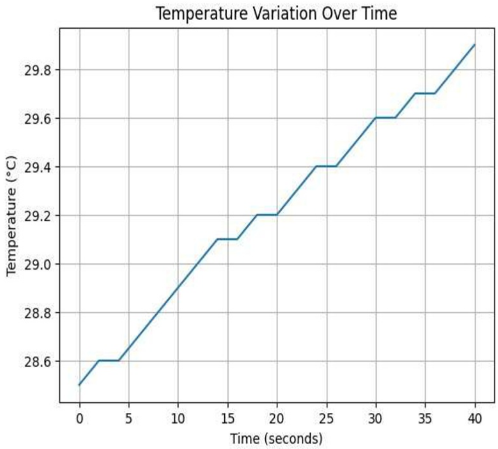

Fig. 3. Temperature Variation Over Time

The Temperature Variation Over Time is shown in Fig.3. The temperature variation observed over time shows a gradual and stable trend throughout the monitoring period. Minor fluctuations in temperature can be attributed to ambient environmental changes and normal heat exchange between the hydroponic system and its surroundings. However, no sudden spikes or drops are observed, indicating that the system operates under controlled conditions.

Maintaining a relatively stable temperature is important in hydroponic cultivation, as temperature directly influences nutrient solubility and root activity. The observed trend demonstrates that the proposed monitoring system is capable of reliably tracking temperature variations in real time, allowing users to identify deviations that may affect plant growth. This confirms the suitability of the system for continuous environmental monitoring in hydroponic applications.

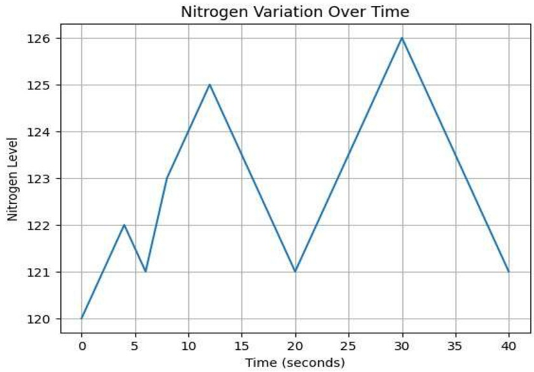

Fig. 4. Nitrogen variation over time

The nitrogen variation over time is shown in Fig. 4. The nitrogen concentration exhibits a gradual variation over the observation period without abrupt fluctuations. This behavior indicates that the nutrient solution remains relatively stable during system operation. Small changes in nitrogen levels can be attributed to normal mixing of the nutrient solution and gradual uptake by plants within the hydroponic setup.

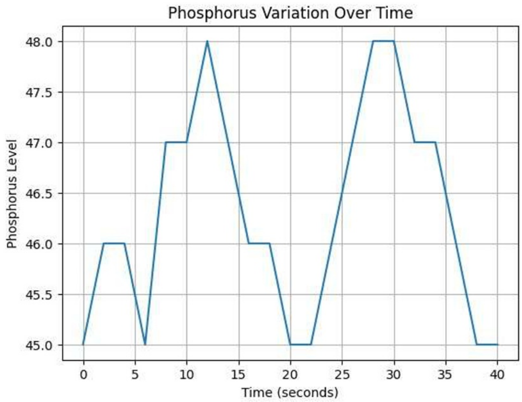

Fig. 5. Phosphorus variation over time

The phosphorus variation over time is shown in Fig. 5. The phosphorus concentration shows a relatively steady trend over the monitoring duration, with only minor variations observed. These small changes can be associated with gradual nutrient utilization within the hydroponic system and natural mixing of the nutrient solution. The absence of sharp fluctuations indicates that phosphorus levels remain within a controlled range during system operation.

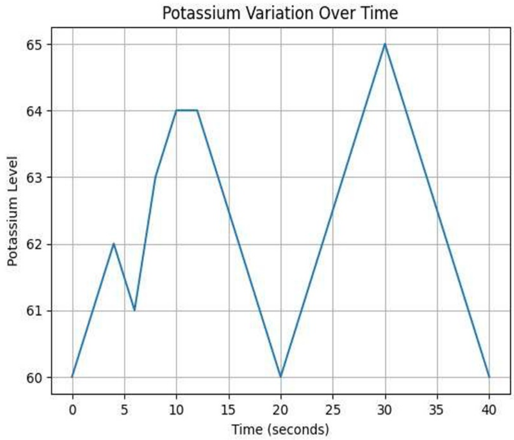

Fig. 6. Potassium variation over time

The potassium variation over time is shown in Fig. 6. Potassium plays a vital role in regulating water balance, enzyme activation, and overall plant metabolism in hydroponic cultivation. The observed trend demonstrates that the proposed monitoring system can reliably track potassium levels in real time, supporting timely identification of potential nutrient imbalances. This highlights the usefulness of the system for maintaining stable nutrient conditions in hydroponic environments

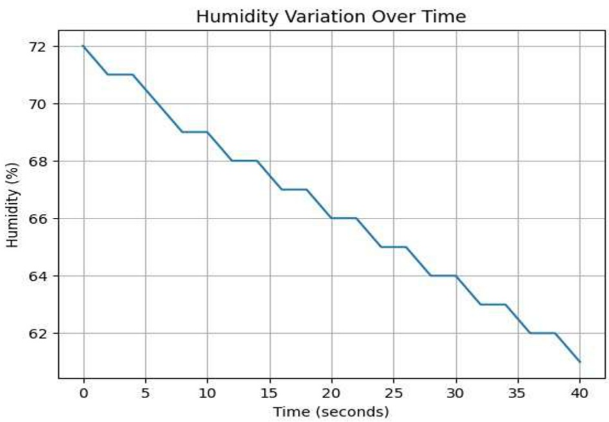

Fig. 7. Humidity Variation over time

The humidity variation over time is shown in Fig. 7. The humidity variation recorded during the monitoring period shows a relatively stable trend with minor fluctuations over time. These small variations are mainly influenced by ambient environmental conditions and normal air circulation around the hydroponic setup. No sudden or extreme changes in humidity are observed, indicating that the system operates under controlled indoor conditions.

The experimental results demonstrate that the proposed IoT-based hydroponic monitoring system is capable of reliably tracking nutrient, environmental, and water-level parameters in real time. The observed trends in nitrogen, phosphorus, and potassium concentrations indicate a stable nutrient environment, while the temperature and humidity measurements show consistent behavior under controlled conditions. In addition, the water-level monitoring using the float sensor ensures continuous awareness of nutrient solution availability. These results confirm that the system operates with stability and consistency over time, validating the effectiveness of the proposed monitoring architecture. Overall, the system provides a practical and low-complexity solution for real-time monitoring in hydroponic applications, making it suitable for small-scale and controlled-environment deployments.

6 CONCLUSION AND FUTURE WORK

The proposed IoT-based hydroponic monitoring system was designed and experimentally evaluated to provide continuous observation of nutrient, environmental, and water-level parameters using a simple and reliable architecture. The results obtained from time-series analysis of nitrogen, phosphorus, and potassium concentrations indicate stable nutrient conditions within the hydroponic system, while temperature and humidity measurements demonstrate consistent environmental behavior under controlled operating conditions. In addition, the inclusion of water-level monitoring through a float sensor enhances system reliability by ensuring continuous awareness of nutrient solution availability.

A key aspect of the proposed work lies in its emphasis on system-level simplicity while maintaining real-time monitoring capability. By employing serial-based data acquisition and web-based visualization, the system avoids unnecessary communication complexity while still delivering timely and meaningful insights into hydroponic operation. This balance between functionality and simplicity makes the proposed approach well suited for small-scale and controlled-environment hydroponic applications.

Future enhancements may include the incorporation of data-driven analysis techniques to support predictive monitoring and intelligent decision-making in hydroponic systems.

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