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Design and Development of an Agricultural Parameter Monitoring System for Hydroponics

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Abstract. The global surge in population, surpassing environmental carrying capacity, poses challenges in ensuring food security, especially in densely populated urban areas. As the demand for food is projected to increase by 60% by 2050, innovative solutions are sought to address constraints like limited land, time, and motivation for traditional agriculture. The study explores hydroponics, a soilless farming method, as a viable solution to enhance food production in confined spaces. Hydroponics involves cultivating plants directly in nutrient-rich water, presenting an efficient and space-saving alternative. The paper details various hydroponic techniques, including Nutrient Film Technique (NFT), Deepwater Culture, and Aeroponics, illustrating their structures and advantages. However, implementing hydroponics in urban settings faces challenges related to time constraints and limited farming knowledge among residents. To address these challenges, the study introduces an innovative PLC-controlled system for hydroponic farming with automated features. The system precisely regulates environmental conditions such as temperature, humidity, water pH, and light intensity through algorithms. Leveraging cloud technology, users can remotely monitor and control the system, ensuring optimal plant growth. An integrated alarm system provides timely alerts, reducing the need for constant physical inspections. The methodology outlines the development stages of the monitoring system, emphasizing the selection of sensors, PLC programming, and integration with the cloud platform. Results indicate successful implementation, with the hydroponic system demonstrating effective communication with the cloud and optimal growth conditions for lettuce. The study concludes with future perspectives, suggesting improvements such as renewable power integration and advanced monitoring features. The proposed automated hydroponic system aims to make urban farming more accessible and manageable, contributing to sustainable and efficient food production.

Key words: Supervisory Control and Data Acquisition (SCADA), Programmable Logic Controller (PLC), Hydroponics, Cloud, Monitoring and Food Scarcity

Introduction

The global population has reached a point where it surpasses the environmental carrying capacity (Pérez Vázquez et al., 2018), leading to various challenges, particularly in urban areas. According to the Food and Agriculture Organization (FAO) prediction, there will be about 9.1 billion people on the planet by 2050, which means food requirements will be 60% more than today. In these densely populated regions, residents often face health and food insecurity issues. Many individuals in urban settings are disinterested in agriculture due to constraints such as limited land space for cultivation, time constraints, and a lack of motivation. However, the pressing issue of food insecurity demands attention. In response to this challenge, individuals, along with the aid of technology, are actively seeking solutions to ensure a reliable and sustainable food supply. The allure of fast food is driven by the numerous innovations in the food industry, often incorporating chemical and unconventional production techniques (Valin et al., 2014).

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The rapid population growth has resulted in an escalating demand for food, outpacing the capacity of current production rates to meet human needs. In response, many farmers resort to the use of synthetic fertilizers to boost plant yields. However, this increased reliance on chemical inputs has consequences, contributing to health issues among individuals living in urban areas due to the consumption of unhealthy foods. The confluence of factors, including high demand, agricultural practices, and dietary choices, underscores the complex challenges associated with modern food systems. Soilless farming, known as hydroponics, presents an ideal solution to address this issue. It presents a new trend in cultivation, especially in confined spaces with limited resources (Jones, 1982). Hydroponics involves growing plants in a water-based system, requiring minimal space for cultivation. The term 'hydroponics' originates from the Greek words 'hydro', meaning water, and 'ponos', meaning labour (Jones, 1982).

Hydroponics essentially involves cultivating plants directly in water. Figure 1 below illustrates various types of hydroponic systems.

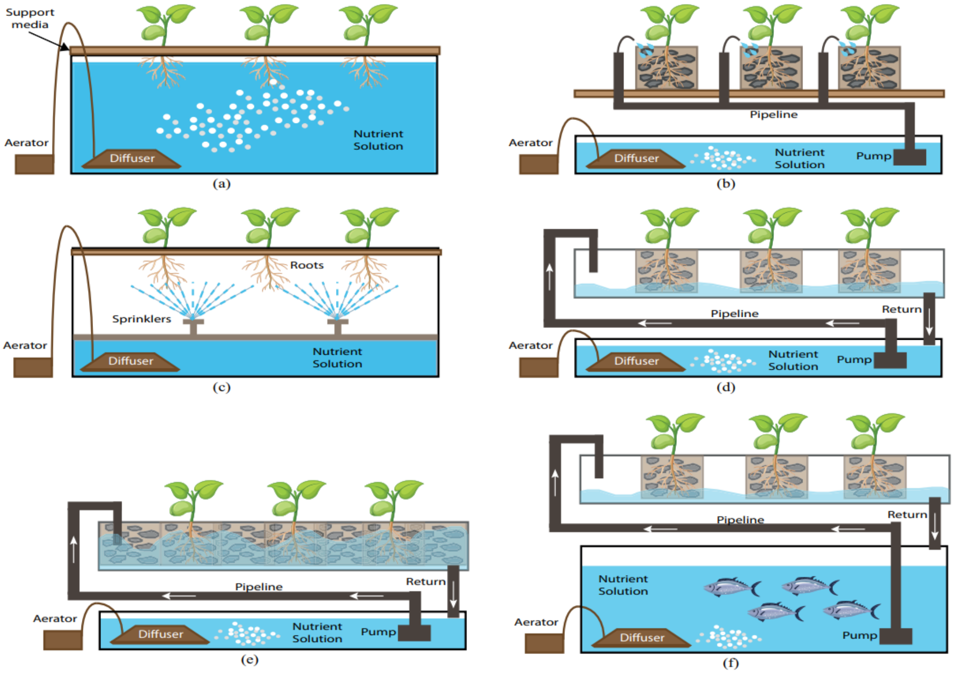

Figure 1. Different types of hydroponic systems (a) Deep Water Culture. (b) Drip System. (c) Aeroponics. (d) Nutrient Film Technique (NFT). (e) Ebb and flow. (f) Aquaponics (Velazquez-Gonzalez et al., 2022)

The nutrient Film Solution (NFT) technique is the most widely adopted form of hydroponics, particularly suited for small and fast-growing plants (Dholwani et al., 2018). In this approach, the nutrient solution is blended with water and directed through a sloping channel. After the process, any excess water is recirculated back to the reservoir (Swain et al., 2021). In the Deepwater technique method, plants are positioned on water mixed with a nutrient solution, with the roots of the plants submerged within the water (Dholwani et al., 2018). In the Ebb and Flow hydroponic technique, plants are placed in trays or containers, filled with a growing medium and nutrient solution mixed with water up to the maximum level. The roots of the plants are submerged in this water mixture (Dholwani et al., 2018). In the Aeroponics cultivation method, plant roots are suspended in the air and a fine mist of nutrient solution is sprayed onto the roots. The mist delivers nutrients and oxygen to the roots, promoting accelerating growth (Swain et al., 2021). Typically, a closed-loop system is used to circulate the nutrient solution in this method. Aeroponics is characterized by a high growth rate and efficient nutrient and water management (Jan et al., 2020). In the hydroponic technique known as drip irrigation, a system of tubes and emitters is employed to deliver a slow, continuous drip of nutrient solution to each plant. The medium, which supports the plants while retaining some moisture, such as perlite, coconut coir, or rock wool, is where the fertilizer solution is drip-fed. The utilization of drip irrigation is versatile and sustainable, suitable for a variety of crops (Dholwani et al., 2018). The Wick system represents the simplest hydroponic system, requiring no electricity, pumps, or aerators. Plants are placed in an absorbent medium such as coco coir, vermiculite, or perlite, with a nylon wick extending from the plant roots into a reservoir of nutrient solution. Water mixed with a nutrient solution is supplied to the plants through capillary action. This system is particularly effective for small plants and herbs (Ali Al Meselmani, 2023).

The primary characteristic of hydroponic systems lies in the provision of essential nutrients for plant growth. These nutrients include crucial elements such as nitrogen, potassium, calcium, boron, magnesium, zinc, and others (Turakne et al., 2021). Typically, these nutrients are mixed with water within the hydroponic system, and the mixture is adjusted based on the pH level of the water. In hydroponic cultivation, the pH level is usually regulated to fall within the range of 5.5 and 6.5 (Ali Al Meselmani, 2023).

This careful control of nutrient composition and pH levels contributes to the optimal conditions for plant development in hydroponic environments.

Hydroponics farming, employing various techniques mentioned earlier, offers a versatile solution that can be implemented virtually anywhere. This innovative method involves growing plants in a soil-less environment, utilizing nutrient-rich water to directly deliver essential minerals to the plant roots. The significance of the system lies in multiple factors. Firstly, it excels in water efficiency, consuming less water for plant production compared to traditional soil-based farming. Secondly, its space efficiency allows for implementation in smaller areas without the need for extensive land. Moreover, the controlled environment in hydroponics mitigates pest and disease pressure, reducing the risk of their spread. Lastly, the year-round production capability is a pivotal advantage, ensuring consistent plant growth independent of seasonal weather patterns.

The conventional hydroponics system faces challenges when applied to indoor cultivation in urban areas, primarily due to time constraints and a lack of farming knowledge among residents. The demands of the hydroponics system, including the precise regulation of temperature, humidity, water pH levels, and light intensity from grow lights, require meticulous attention to achieve optimal results. However, individuals in urban settings often struggle to dedicate the necessary time to these tasks. Additionally, the limited knowledge of farming practices further complicates the successful implementation of hydroponics, leading to initial failures in many attempts. Addressing these practical constraints is crucial for making hydroponics more accessible and feasible for urban dwellers.

To address the challenges of time constraints and limited farming knowledge in urban areas, technology offers an innovative solution through automated hydroponics systems. These systems utilize algorithms to control various environmental conditions, including temperature, humidity, water pH levels, electrical conductivity, and light intensity. While automation minimizes the need for constant manual intervention, the possibility of errors still exists. To mitigate this, the paper proposes a monitoring solution for hydroponic systems. This solution aims to provide a streamlined and efficient means of overseeing and ensuring the optimal functioning of the hydroponics setup, reducing the reliance on individuals to continuously inspect and troubleshoot system conditions.

The objective of this project is to conduct a thorough and comprehensive parametric monitoring of the hydroponic system. This involves a detailed examination of various parameters associated with hydroponic cultivation. The overarching goal is to identify and finalize monitoring features crucial for ensuring efficient oversight of the system. This study is an integral part of a broader project that aims to enhance the automation and efficiency of hydroponic farming. The project specifically addresses challenges arising from limited time and knowledge in urban settings, seeking to make hydroponic cultivation more accessible and manageable for individuals in such environments.

This study introduces an automated PLC-controlled system designed to execute an algorithm that precisely balances various environmental conditions within an indoor hydroponics system. The system manages factors such as room humidity, water temperature, room temperature, pH levels, and the light intensity of grow lights. Achieving this equilibrium empowers users with the ability to remotely monitor and control the system from any location worldwide. Leveraging cloud technology, users can log into a dedicated platform to observe the system's status and enact control measures as necessary. An integrated alarm management system ensures users receive timely alerts through a mobile app, eliminating the need for constant physical inspections. This technology enables users to seamlessly integrate hydroponic farming into their daily routines, fostering a convenient and efficient indoor cultivation experience.

The remainder of this paper follows a structured outline. The section 2 delves into the literature survey, providing an overview and insights relevant to the subject. Section 3 offers an in-depth exploration of the detailed methodology employed in the development of the monitoring system. Moving forward, Section 4 concentrates on the results and discussion, summarizing key findings and engaging in a thoughtful analysis of the study's implications. Finally, section 5 serves as the conclusion of the paper, outlining the key takeaways and paving the way for future directions in research and application within the scope of the discussed hydroponics system monitoring.

Literature Review

Akinmeji and Misra implemented a monitoring system using an AT-Mega 328 microcontroller powered by a 5V DC source. This system was designed to collect data from various sensors, including those measuring water temperature, light intensity, water pH, and electrical conductivity. The collected data were then transmitted to a LabVIEW interface. Serial communication (USART) facilitated communication between the microcontroller and LabView interface, allowing for real-time monitoring of the system's characteristics. PID controllers were employed to control hardware output components based on the input data (Akinmeji et al., 2022).

While this approach offers the advantage of using cost-effective and widely available microcontrollers, it comes with certain limitations. Microcontrollers are considered less reliable than PLC systems, and the data transfer speed is slower in real-time control scenarios, potentially leading to connection issues. Moreover, the monitoring system must remain constantly connected to a computer for the monitoring and control procedures to be completed. Additionally, open-source applications like LabVIEW may not provide full user control (Akinmeji et al., 2022). Adhau, Surwase, and Kowdiki utilized an AVR microcontroller and LabVIEW for autonomous control of hydroponic systems. Arduino-based sensors collected data for humidity, temperature, and light intensity, controlled by PID controllers. The connection between the AVR microcontroller and LabVIEW was through the USB port, but drawbacks include the need for pre-parameter adjustments and limited remote monitoring capabilities (Adhau et al., 2018).

In another study, Arduino-based devices using the MQTT method were implemented for data exchange in vegetable plantations, monitoring light intensity, water level, and product quality. The system was accessed through LAN-connected PCs (Velazquez-Gonzalez et al., 2022).

An automated PLC-based research study utilized the ILC 1712TX PLC and HMI for monitoring and controlling six chambers. PC Worx software adjusted electrical conductivity, humidity, and pH levels, with HMI touch panels monitoring and managing environmental factors. A web-based touch panel with profinet communication facilitated HMI construction for automation (Wagh Vijendra Pokharkar et al., 2016).

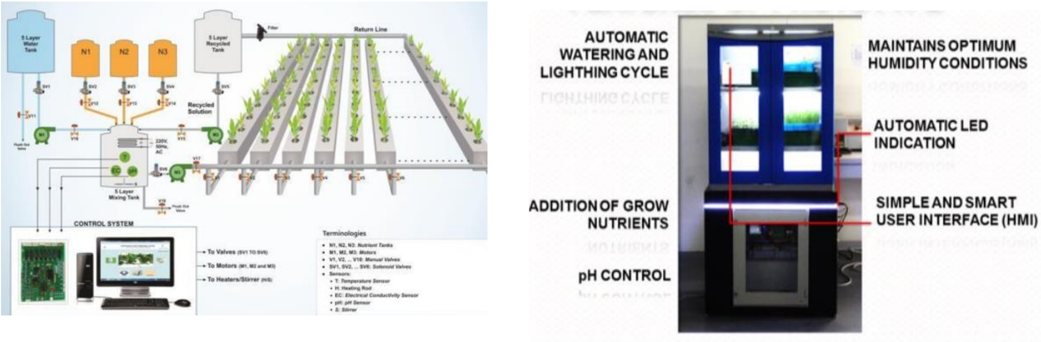

Figure 2. Previous PLC Controlled Systems (Wagh Vijendra Pokharkar et al., 2016), (Francy et al., 2016)

In summary, while microcontroller and Arduino-based systems offer cost-effective solutions, they come with limitations in terms of reliability, real-time control, and remote monitoring capabilities. On the other hand, PLC-based systems provide more robust control and monitoring but may have drawbacks in terms of constant computer connectivity. The choice between these technologies depends on specific project requirements and the trade-offs deemed acceptable for the intended application. Future improvements could focus on addressing the limitations observed in each approach, such as enhancing the reliability of microcontroller-based systems or improving remote accessibility in PLC-based systems (Kanishka Tharindu Rathnayake & Tharaga Sharmilan, 2023).

Methodology

In this section, the methodology of the system is discussed, starting from its initial stages. The process commences with the presentation of a block diagram, illustrated in Figure 1, providing an overview of the system's structural components and their interconnections.

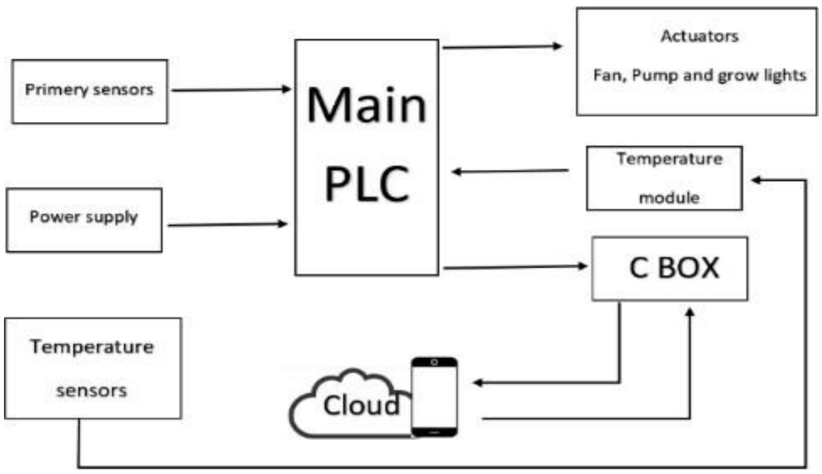

Figure 3. Block diagram of the system

The primary objective of this study is to develop an advanced farming method aligned with the latest technology, specifically tailored for urban residents. Key considerations for the solution encompass its ability to fit within small household spaces, ensuring a Return on Investment (ROI), generating passive income to offset costs of acquiring equipment like PLC and allowing for the system expansion. Versatility is crucial, with the system designed to accommodate various plant types. Moreover, the emphasis is on low energy consumption and minimal data usage for optimal efficiency. With the finalization of these solution parameters, the study identifies key parameters requiring regulation within the system. These include room temperature, water temperature in the system, water pH levels, light intensity for plant growth, and room humidity. The subsequent step involves selecting the ideal automation technique for indoor applications, with the NFT being chosen. A SolidWorks design was modelled to showcase the final system design, providing insights for sensor placement, as depicted in Figure 2.

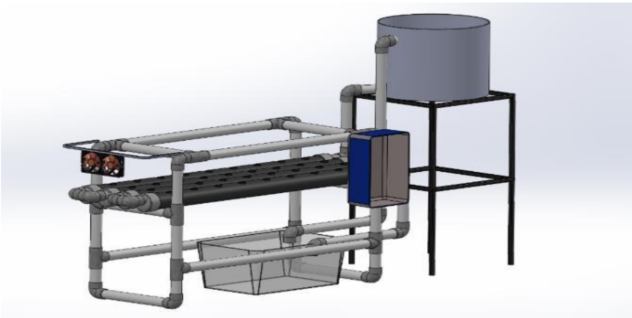

Figure 4. Designed NFT Hydroponics system

The sensor integration process for the system involved finalizing sensor selections and creating a PLC ladder diagram based on the specific requirements of the plants. Through a systematic approach, the program was iteratively improved by testing sensors under actual conditions. Once all sensors were identified, the next step involved determining the communication method between the PLC and the sensors.

Since not all sensors provided digital output, the Modbus protocol linked the humidity and temperature sensors to the PLC. The chosen pH sensor, being Arduino-based, required the incorporation of an Arduino program into the system. Subsequently, Modbus master serial communication relayed input values from the Arduino to the PLC's internal registry. Figure 3 illustrates the PLC programming software and the ladder diagram, showcasing the integration and communication framework of the entire system.

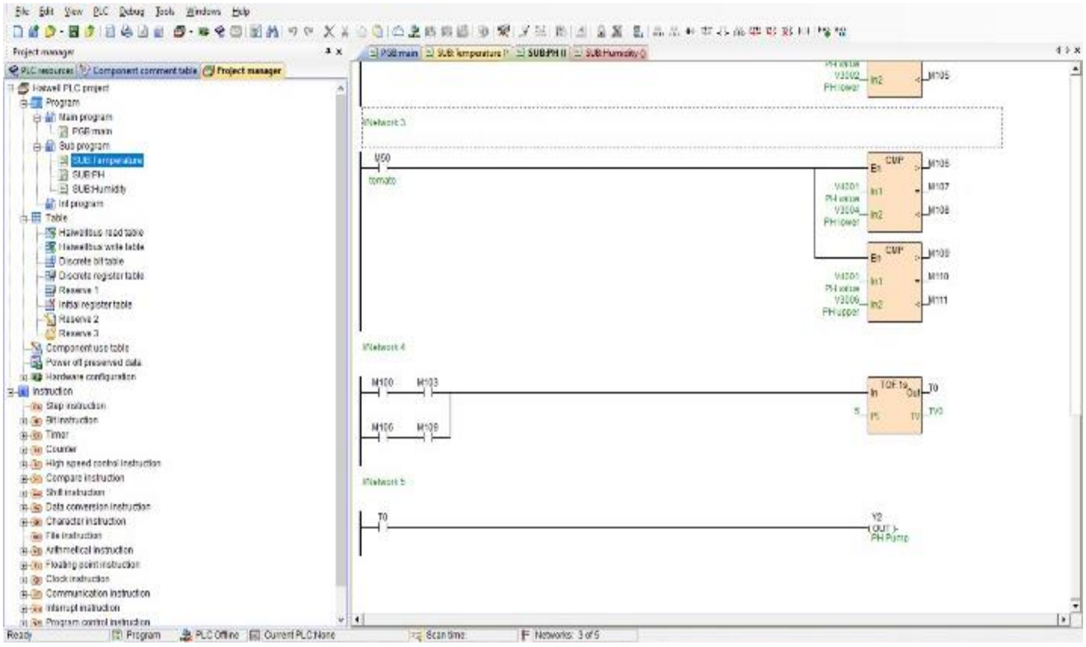

Figure 5. Integration and communication framework of the entire system

The finalized system design predominantly utilized PVC for constructing the system frame and the containers for plantation pots. The hardware components employed on the system include the main PLC (AT12MOT) responsible for data acquisition and control in accordance with the ladder diagram. Additionally, an H04TC PLC extension was integrated to facilitate temperature sensor readings. The CBOX served as the connection point between the PLC and the WAN (Wide Area Network), ensuring network connectivity. A 24V power supply was employed to provide the necessary power to the entire system.

In terms of sensor selection, a K-type thermocouple was utilized to measure water temperature, while a rod-type Arduino-based pH sensor was employed to measure the system's pH value. For monitoring room temperature and humidity levels, an RS-WS-N01-2 humidity sensor was chosen. Lastly, a level sensor was incorporated to measure the water level within the reservoir tank. These carefully selected sensors contribute to the comprehensive monitoring and control capabilities of the hydroponic system.

Following the PLC ladder diagram, the monitoring interface was crafted as a SCADA platform. Within the SCADA software, distinct pages were created to list and display various environmental parameter inputs and outputs for parameter settings, each corresponding to different parameters. These pages serve as dedicated sections for monitoring different aspects of the hydroponic system.

The SCADA interface allows users to adjust environmental conditions based on their preferences. Users can modify parameters such as pH levels, temperature settings, light intensity, bulb height relative to plants, bulb on/off timings throughout the day, manual control of the bulb, manual dosing pump operation, main pump control, and humidity level set points. Additionally, the interface offers pre-installed parameter settings tailored for various plant types, facilitating ease of use and adaptability to different cultivation needs. This comprehensive and user-friendly interface enhances the system's flexibility and control, empowering users to tailor the hydroponic environment to specific plant requirements.

The cloud platform was designed using the Haiwell cloud platform, creating a secure personal cloud space with a username and password linked to the user's Gmail address. Within this personalized cloud space, the Haiwell cloud platform facilitated the upload of the designed SCADA interface by connecting the PLC to the internet. Subsequently, the uploaded project on the cloud platform required configuration, including the assignment of a working IP address and adjustments to parameters based on the specific project requirements. This configuration was executed through the PLC, ensuring synchronization between the local system and the cloud platform.

The next step involved the connection of the PLC with the Haiwell cloud, utilizing the data registries inside the PLC and matching them with the uploaded program. To access and configure the system remotely, a mobile app was employed. The app connected to a personal hotspot created through the PLC and identified LAN devices. Once the device was located, the system configuration allowed the PLC to connect to the home Wi-Fi or any available data connection. Using the mobile app, the WAN access of the uploaded project and device was identified, enabling the configuration of parameters such as alarm management, security options, and accessibility for other users. This integrated cloud platform ensures seamless remote monitoring and management of the hydroponic system, enhancing accessibility and control for users.

Results and Discussion

In Figure 6, we present the visualization of monitoring system data, while Figure 7 provides a compact system overview.

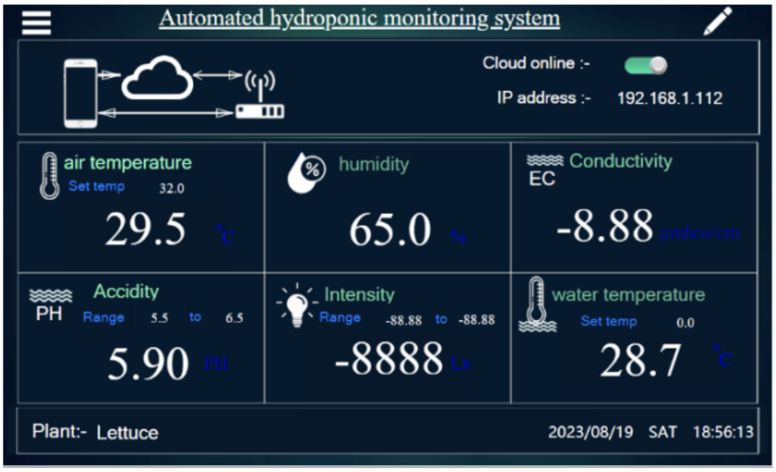

Figure 6. Visualization of monitoring system data

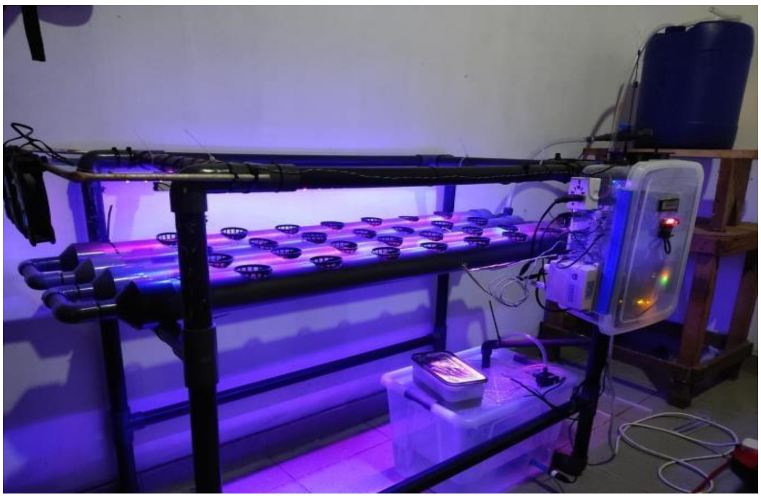

Figure 7. Compact system overview

After successfully connecting all sensors and devices to the cloud, the hydroponic system was implemented and tested with actual plants, specifically lettuce. The automated hydroponic system demonstrated effective communication with the cloud platform, running smoothly to create optimal environmental conditions for plant growth. Over 70 days, the lettuce exhibited proper growth, with all monitored parameters adjusting correctly.

As a system is fully automated, user interaction is minimal once the planting process is complete. However, a challenge arose during the nutrient solution addition process due to communication delays between the PLC and Arduino board. To address this issue, a logical timer and a slow mixer were integrated into the system. This addition prevented over-dosing of the nutrient solution by activating the logical timer and slow mixer after the initial 20ml nutrient solution addition. This approach, coupled with continuous pH sensor readings, effectively resolved the over-dosing problem.

The Wi-Fi capability of the PLC with the cloud platform opens up possibilities for diverse projects, enabling monitoring and control processes for any automated network. The system accommodates unlimited users within the same network, proving the advantage of remote monitoring and control from anywhere globally.

Data storage on the cloud platform facilitates analysis and assessment of system effectiveness. Additional features such as webcam visualization for plant status and robotic arms for pest control and leaf removal can be implemented without limitations.

Looking ahead, future perspectives include integrating renewable power sources into the system. Further enhancements to the monitoring feature involve incorporating grow light height regulation based on plant age and height, implementing image processing for identifying plant abnormalities and pests, and developing a more user-friendly graphical 3D design monitoring system. These advancements signify a forward-looking approach to improving sustainability, efficiency, and user experience in hydroponic farming.

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