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Automated Hydroponic System with Optimized Plant Growth Light Spectrum for Sustainable Indoor Agriculture

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Abstract: This paper presents the design and development of an automated hydroponic system that integrates real-time monitoring and control of environmental parameters along with spectrum-optimized plant growth lighting to enhance crop yield in indoor farming environments. The system utilizes an Arduino Uno microcontroller to control pH, electrical conductivity (EC), water level, and temperature, while a spectrum-adjustable LED light setup provides suitable lighting conditions for different stages of plant growth. Sensors continuously monitor environmental conditions and transmit data to the controller, which adjusts nutrient supply and lighting accordingly. The structure is built using PVC channels with an efficient water circulation system to minimize wastage. Experimental results demonstrate improved growth rates, efficient nutrient utilization, and reduced water consumption compared to conventional soil-based farming methods. This smart hydroponic system offers a scalable and eco-friendly solution for sustainable urban agriculture, particularly in areas with limited arable land.

Keywords: Hydroponics, Smart Agriculture, Plant Growth Spectrum, Indoor Farming, Sensor-Based Monitoring, LED Grow Lights.

I. INTRODUCTION

The growing global population and rapid urbanization have intensified the demand for sustainable agricultural practices that can operate efficiently within limited spaces and resource constraints. Traditional soil-based farming is becoming increasingly unsustainable due to land degradation, water scarcity, and climate unpredictability [1]. In this context, hydroponics soilless cultivation of plants using mineral nutrient solutions in a water solvent has emerged as a promising alternative for modern agriculture [2].

Hydroponic systems offer numerous advantages such as higher yield, faster plant growth, and reduced water and nutrient usage compared to traditional agriculture [3]. These systems are especially beneficial in urban and arid regions where arable land and fresh water are scarce. However, maintaining optimal growing conditions in hydroponics requires constant monitoring and precise control of several parameters, including pH, electrical conductivity (EC), temperature, and light spectrum [4].

Recent advancements in automation and embedded systems have enabled the development of intelligent hydroponic systems that can autonomously regulate these parameters in real time. Microcontrollers like the Arduino Uno, paired with various sensors and actuators, provide an affordable and effective means of implementing such control mechanisms [5]. Additionally, the use of artificial light particularly LED grow lights has become an essential component of indoor hydroponic systems, enabling year-round cultivation by mimicking natural sunlight [6].

The plant growth spectrum plays a critical role in photosynthesis, flowering, and fruiting. Studies have shown that specific wavelengths, such as blue and red light, significantly influence plant morphology and productivity [7]. Incorporating adjustable spectrum LED lighting allows growers to optimize light conditions for different growth stages, further improving plant health and yield.

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This paper proposes the design and implementation of an automated hydroponic system integrated with a spectrum-controlled lighting setup. The system monitors environmental conditions in real-time using sensors and applies feedback control via an Arduino-based system to maintain optimal growth conditions. The aim is to create a scalable, cost-effective, and environmentally sustainable solution for indoor agriculture, particularly suited for urban households, research centers, and vertical farming applications.

II. LITERATURE REVIEW

Hydroponic farming systems have garnered significant interest due to their capacity to address land scarcity and water conservation while maximizing crop yield [1]. Resh (2012) provides comprehensive guidance on hydroponic food production, covering nutrient solutions, system designs, and crop management strategies [2]. His work laid the foundation for advanced and automated hydroponic systems.

Gruda (2009) discussed the impact of soilless culture on the quality and nutritional value of vegetables, revealing that hydroponic crops often exhibit better uniformity and shorter growth cycles compared to traditional soil-based cultivation [4]. These findings highlight the potential of hydroponic methods in producing high-quality vegetables in urban environments.

Recent studies have shifted focus toward integrating automation and IoT (Internet of Things) technologies into hydroponic systems. Nayak et al. (2018) developed an automatic hydroponic system using Arduino and IoT, which monitored and controlled water level, pH, and nutrient concentration in real-time [5]. Their findings emphasized the advantages of automation in reducing manual labor and increasing system efficiency.

In terms of lighting, Singh et al. (2015) and Morrow (2008) explored the role of LEDs in greenhouse and indoor agriculture. Singh et al. highlighted the energy efficiency and spectral flexibility of LEDs, enabling precise manipulation of plant growth factors such as flowering and photosynthesis [6]. Morrow's work further confirmed that LED lighting promotes faster growth rates and reduces electricity consumption, making it ideal for controlled environments like hydroponic farms [7].

Furthermore, Muhammad Niswar (2024) reviewed hydroponic applications in developing countries, identifying automation as a vital factor for scalability and consistent output [8]. They emphasized the need for cost-effective solutions involving microcontrollers like Arduino to ensure affordability and accessibility.

These studies collectively indicate that combining hydroponic systems with automation and energy-efficient lighting creates a promising pathway for sustainable agriculture. However, there remains a gap in fully integrated systems that use Arduino for dynamic LED control based on plant needs an area this research aims to address.

IV. SYSTEM DESIGN

The development of the Automated LED Light Controlled Hydroponic System involves the integration of various hardware and software components to achieve optimal plant growth in a controlled, soilless environment. The methodology incorporates the use of Arduino Uno for system control, along with sensors and LED lighting systems for automation. The system is designed to monitor and adjust essential parameters such as water level, pH, and light spectrum, ensuring that plants receive the optimal conditions for growth.

3.1 System Architecture

The system is built around an Arduino Uno microcontroller, which serves as the central unit for controlling all operations. The architecture consists of the following components:

- ❖ The Arduino Uno serves as the core controller that processes data from sensors and activates relevant actions, such as turning on the water pump or controlling the LED light spectrum.
- ❖ The water pump is controlled by the Arduino to maintain water flow in the hydroponic channels based on sensor readings.
- ❖ The water level sensor continuously monitors the water level in the nutrient tank. If the level drops below a certain threshold, the system triggers an alert using a buzzer.
- ❖ The pH sensor, mounted on a servo motor, measures the pH level of the nutrient solution in the tank. If the pH level falls outside the ideal range for plant growth, the system alerts the user and activates a pH correction mechanism.

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- The LED light spectrum control uses a combination of white, pink, and green LEDs, with each color representing a specific wavelength range to support different stages of plant growth (e.g., blue for vegetative growth and red for flowering).
- The servo motor adjusts the position of the pH sensor for periodic readings, extending the sensor's lifespan and ensuring accurate data collection.
- The buzzer acts as an audio feedback mechanism that signals when the water level is low or when pH correction is required.

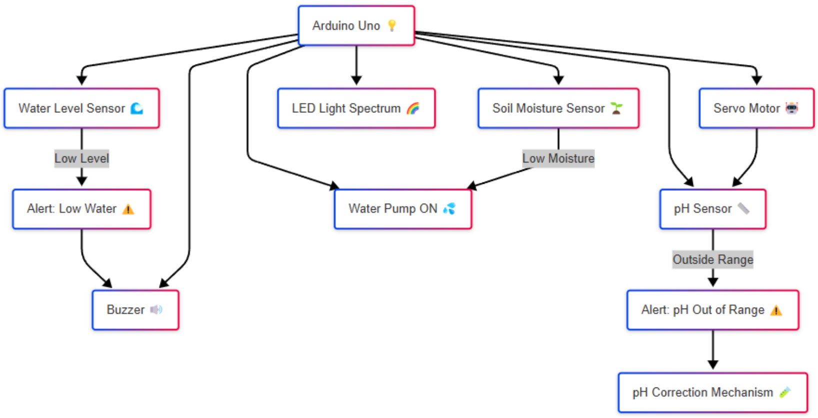

Figure 1: System Architecture

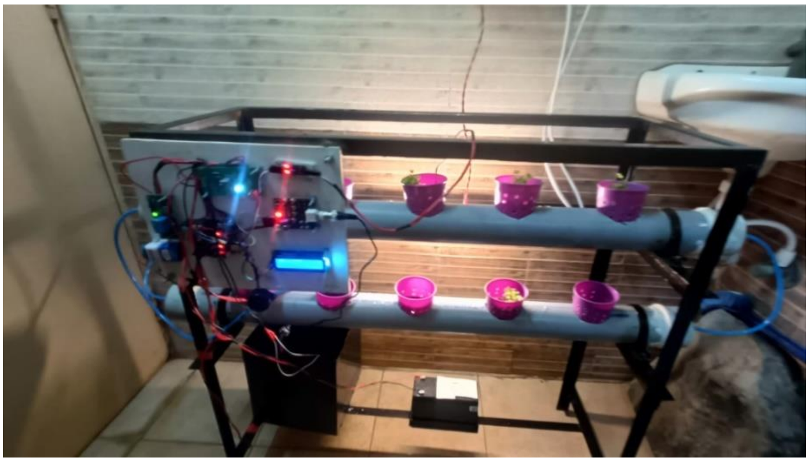

Figure 2: Hydroponic System under Full-Spectrum White LED Light

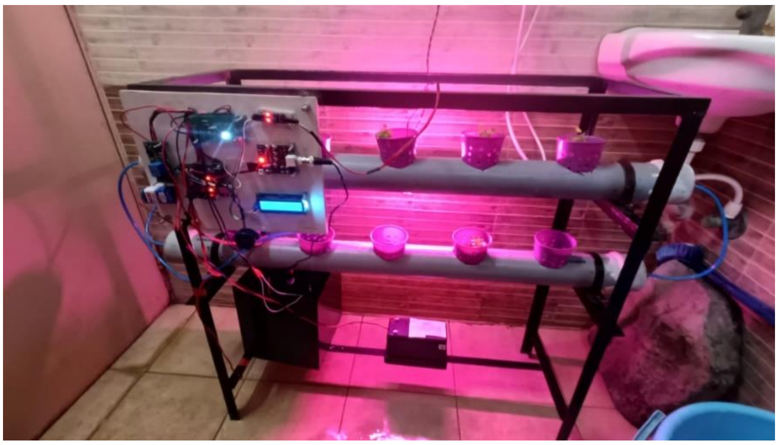

Figure 3: Hydroponic System under Pink LED Light

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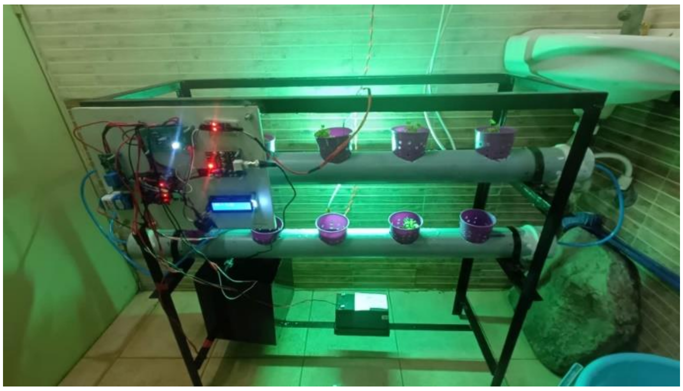

Figure 4: Hydroponic System Under Green LED Light

3.2 Hardware Components

The system uses several key hardware components:

- The Arduino Uno microcontroller is responsible for processing inputs from the sensors and controlling the actuators such as the water pump, servo motor, and LEDs.
- The water level sensor is a simple float switch that measures the water levels in the system.
- The pH sensor is an analog sensor that measures the acidity or alkalinity of the nutrient solution.
- LED lights in red, blue, and white are used to simulate sunlight and optimize different stages of plant growth. The lighting system is programmable to adjust light intensity and spectrum based on the plant's growth phase.
- The servo motor, attached to the pH sensor, moves the sensor periodically to ensure accurate readings.
- The water pump is used to circulate the nutrient solution within the hydroponic system and is controlled by the water level sensor.

3.3 Software Development

The software controlling the system is written in Arduino C/C++ and functions as follows:

- The system continuously collects data from the water level sensor and pH sensor. The readings are processed by the Arduino microcontroller.
- If the water level drops below a specified threshold, the system activates the water pump to restore the water level. Similarly, if the pH sensor detects that the pH is outside the optimal range, the system triggers a corrective action.
- The system employs time-based and sensor-based adjustments to control the LED light spectrum. During the day, the LEDs emit a white light, while at night or for specific growth phases, pink or blue LED lights are activated to simulate the natural sunlight spectrum.
- When the water level is low or the pH level needs adjustment, the system activates the buzzer, alerting the user to refill the tank or correct the nutrient solution.

3.4 Automation and Control Logic

The system is fully automated, reducing the need for manual intervention. The control flow can be summarized as follows:

- The water level sensor continuously checks the nutrient tank. If the water level is insufficient, the water pump is activated until the correct level is restored.
- The pH sensor mounted on the servo motor periodically measures the pH level of the nutrient solution. If the pH deviates from the ideal range, the system triggers an alert to the user.
- The system uses programmed light cycles to simulate different growth phases. For example, blue LEDs are used to promote vegetative growth, while red LEDs are used for flowering. The light intensity is dynamically adjusted based on the stage of plant growth.
- While this system is primarily automated, future improvements could include a mobile app or web interface for remote monitoring and control of parameters like pH, water level, and light intensity.

3.5 Prototype Development and Testing

A prototype of the system was developed using standard off-the-shelf components. The system was assembled, programmed, and tested in a controlled environment. Initial tests confirmed that the system could successfully regulate water levels, maintain optimal pH, and control LED light spectra for various plant growth stages. During testing, the system demonstrated the following:

- The water pump was successfully triggered based on water level readings.

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- The pH sensor provided accurate readings, and the servo motor ensured periodic measurements.
- The LED lighting system was responsive to changes in plant growth needs.

Future iterations will focus on refining the control algorithms and integrating advanced IoT capabilities, allowing for remote monitoring and management of the hydroponic system.

IV. RESULTS AND DISCUSSION

The automated LED light-controlled hydroponic system was evaluated through a series of tests to determine its effectiveness in optimizing plant growth conditions and its reliability in automating critical parameters such as water levels, pH, and light spectrum. The results of these tests are presented and discussed below.

4.1 System Performance

The system was tested with several plants over a period of four weeks. The key performance indicators (KPIs) included water level regulation, pH maintenance, and light control.

Water Level Regulation

- The water level sensor performed consistently, triggering the water pump whenever the water level dropped below the threshold. This ensured that the plants received a constant supply of nutrients, preventing root dehydration.
- The system's response time was rapid, and the water pump effectively replenished the nutrient solution within minutes.

pH Regulation

- The pH sensor provided continuous real-time data, allowing the system to detect any deviations in the nutrient solution's pH levels. The servo motor mechanism ensured periodic sensor calibration, leading to accurate and timely measurements.
- During the testing phase, the system was able to detect slight pH changes and activate a buzzer alert when the pH level fell outside the optimal range for plant growth. However, no automatic pH correction mechanism was integrated, meaning manual intervention was still required to adjust the pH, which could be a point for future enhancement.

Light Spectrum Control

- The LED system worked as expected, adjusting the light intensity and spectrum based on the pre-programmed schedule. Blue light was provided during the vegetative growth phase, and red light was used to encourage flowering. White light was used during the day to mimic natural sunlight.
- Light intensity was adjusted automatically based on the time of day, promoting optimal photosynthesis. The system successfully simulated natural light cycles, with the light intensity gradually decreasing in the evening and increasing again in the morning.

4.2 Plant Growth Analysis

To evaluate the system's effectiveness in fostering plant growth, a set of plants was grown using the hydroponic system, and their growth was compared to plants grown in a traditional soil-based system.

- The plants grown in the hydroponic system exhibited a significantly faster growth rate, with visible improvements in height and leaf size compared to the soil-based plants. The optimal light conditions and nutrient availability played a key role in promoting faster growth.
- Hydroponically grown plants displayed a healthier, more vibrant green color compared to their soil-based counterparts, indicating improved nutrient absorption.
- The roots of the hydroponically grown plants were well-developed, with no signs of rot or dehydration, suggesting that the water and nutrient solution was maintained at appropriate levels.

4.3 System Efficiency

The efficiency of the automated system was assessed in terms of energy consumption, water usage, and user interaction.

- The system used a low amount of power, primarily due to the efficient LED lighting system, which consumed significantly less energy compared to traditional lighting methods. The water pump and servo motor consumed minimal power, as they were activated only when needed.
- The hydroponic system demonstrated efficient water use, with no water wastage due to evaporation or drainage. The recirculation of water through the system ensured that the plants received adequate hydration without the need for frequent refills, thus conserving water.

- The system was largely automated, reducing the need for manual monitoring. The only user interaction required was occasional monitoring of the pH levels and refilling the nutrient tank. Future improvements could include integrating an automatic pH correction system and a mobile app for remote monitoring.

4.4 Challenges and Limitations

While the system performed well, several challenges were encountered during the testing phase:

- As mentioned, the system alerts the user when the pH level falls outside the optimal range but does not automatically adjust it. Future developments could include a mechanism to automatically add pH adjustment solutions to the nutrient tank.
- Regular calibration of the pH sensor and water level sensor is required to ensure accurate readings. Without proper calibration, sensor drift can lead to inaccurate readings, which may affect the system's performance.
- The current system is designed for small-scale hydroponic setups. Scaling the system for larger operations will require more advanced control algorithms and additional hardware to monitor and manage multiple growth stages, environmental factors, and plant types.

4.5 Future Work and Improvements

Several improvements can be made to enhance the functionality and efficiency of the hydroponic system:

- Future versions of the system could include an automatic pH correction system that adjusts the pH level in real-time based on the sensor data, reducing the need for manual intervention.
- Incorporating Internet of Things (IoT) capabilities could allow users to remotely monitor and control the system through a mobile app or web interface. This would make it easier for users to manage their hydroponic systems without needing to be physically present.
- The integration of advanced light sensors and more sophisticated algorithms could enable the system to adjust the light spectrum dynamically based on the plant's growth stage, time of day, and environmental conditions.
- To cater to larger hydroponic farms, the system could be expanded to manage multiple tanks and grow beds, integrating sensors and controllers for various environmental factors such as temperature, humidity, and CO_2 levels.

V. CONCLUSION

This study successfully designed and implemented an automated LED light-controlled hydroponic system that integrates sensors and actuators to regulate key environmental factors essential for plant growth. The system proved to be effective in automating the management of water levels, pH, and light intensity, thereby significantly reducing the need for manual intervention. Real-time monitoring allowed the system to respond promptly to changes in environmental conditions, ensuring that plants received optimal growth conditions throughout their development stages. The results showed that the hydroponic system promoted faster and healthier plant growth compared to traditional soil-based methods. The plants exhibited enhanced root development, improved leaf color, and accelerated growth rates, demonstrating the effectiveness of the controlled environment provided by the system. Additionally, the system was highly resource-efficient, utilizing energy-efficient LED lights and a recirculating water system to minimize energy consumption and waste. However, the study also identified some challenges, including the need for regular calibration of sensors and the absence of automatic pH adjustment, which required manual intervention. These areas of improvement indicate that while the system is promising, further advancements are necessary to enhance its precision and reduce the reliance on human monitoring. The automated hydroponic system represents a viable and efficient solution for modern agriculture, particularly in environments with limited space or water resources. With future improvements such as automatic pH correction, IoT integration, and scalability for larger setups, the system could serve as a foundational model for sustainable and automated farming practices, making hydroponics more accessible and practical for both small-scale and commercial applications.

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