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Prototype of Hydroponic Lettuce Cultivation: IoT-Based Automatic Irrigation System for Growth Enhancement and Sustainability

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***Abstract*— Lettuce (Lactuca sativa) is a vegetable commonly grown in temperate and tropical climates. In organic cultivation, lettuce has high economic value due to its high mineral content, including iodine, copper, iron, phosphorus, and others. Hydroponics is an agricultural cultivation method that uses water as the planting medium. This method offers advantages such as space efficiency and more. Currently, monitoring water in hydroponic plant cultivation is conducted periodically by growers who physically visit the cultivation site, including the reservoir tank. This process can be quite inconvenient because growers cannot predict when moisture levels will drop. One solution to this problem is to implement remote, real-time water monitoring for hydroponic lettuce cultivation using Internet of Things (IoT) devices. Therefore, a system design for IoT-based remote monitoring of moisture levels is required, allowing growers to monitor the condition of hydroponic lettuce without needing to visit the cultivation site. The research findings indicate that when the moisture level is dry, the system will display a value of 100, prompting users to receive a notification for irrigation. If the value is below 100, the system indicates that the planting medium is sufficiently moist.**

Keywords*— *Hydroponics, Lettuce, IoT, Moisture

I. INTRODUCTION

Hydroponic cultivation is one of the promising modern agricultural solutions, especially in addressing the challenges of land and water availability [1]. In the context of urban farming, lettuce *(Lactuca sativa)* is one of the most commonly cultivated plants due to its short life cycle and high economic value [2]. Lettuce *(Lactuca sativa)* is a vegetable commonly grown in both temperate and tropical climates. In organic farming, lettuce holds significant economic value due to its high mineral content, including iodine, copper, iron, phosphorus, and more. It is renowned for its fiber content and essential nutrients such as vitamins and minerals [3]. Hydroponic lettuce cultivation has gained popularity because of its efficient use of land and resources. Hydroponics is a farming technique that utilizes water as the growing medium instead of soil [4]. This method reduces the space required for cultivation while producing high-quality and high-yield crops compared to traditional soil-based farming.

Hydroponics represents a modern agricultural approach that efficiently utilizes resources and has the potential to boost sustainable crop production. In hydroponic systems, lettuce plants are grown without soil, with their roots submerged in nutrient-rich solutions containing essential elements like nitrogen, phosphorus, potassium, and other minerals required for healthy growth [5]. Water serves as the primary medium, often complemented by substrates like sand, gravel, or plant fibers to support the roots.

Traditionally, water monitoring in hydroponic systems has been conducted manually by growers visiting the cultivation site. This manual process can be labor-intensive and inefficient, as growers cannot always detect when humidity levels drop. A promising solution is real-time remote monitoring of hydroponic lettuce cultivation using Internet of Things (IoT) technology [6]. The Internet of Things (IoT) refers to a network of physical devices, such as sensors, vehicles, and appliances, equipped with technology to collect and exchange data via the internet. IoT allows devices to communicate, share information, and coordinate actions without direct human intervention [7]. With continuous technological advancements, IoT is expected to play a crucial role in transforming various sectors, including agriculture. Designing an IoT system capable of remotely monitoring humidity levels in hydroponic lettuce cultivation can significantly reduce labor and enhance productivity.

In the rapidly evolving technological landscape, IoT applications have contributed significantly to improving efficiency and productivity across various domains, particularly agriculture [8]. One area of interest is the development of automated irrigation control systems for hydroponic lettuce cultivation. This technology addresses the challenges associated with plant care, especially in hydroponic farming.

The use of Internet of Things (IoT) technology offers an innovative solution for managing hydroponic systems. By utilizing IoT, monitoring and control processes can be performed automatically and with precision [9]. IoT technology presents significant opportunities for resource optimization through real-time and highly accurate environmental monitoring. With the integration of IoT devices, hydroponic systems can not only reduce water usage but also minimize the need for human labor [10].

Previous studies have shown that the use of IoT-based technology can increase crop yields by up to 25% across various types of horticultural plants. On the other hand, sustainability is also a key aspect of the development of this technology-driven hydroponic system. Through more efficient management, IoT technology can support environmentally friendly farming practices that are adaptive to climate change [11].

Hydroponics is an advanced farming technique that replaces traditional soil with water as the growing medium, reducing land usage while enabling the production of high-quality crops [12]. This method enhances resource efficiency and provides a reliable way to cultivate crops like lettuce. In traditional hydroponic systems, water monitoring is typically done manually, requiring growers to visit the cultivation site regularly. However, this method is inefficient and time-consuming, as moisture levels can fluctuate unexpectedly, making it difficult to anticipate irrigation needs .

In response to this issue, IoT (Internet of Things) technology offers a promising solution by enabling real-time [13], remote monitoring of water levels. IoT refers to a network of interconnected devices that collect and exchange data through the internet, allowing for remote management and control. The integration of IoT technology into hydroponic systems can automate irrigation, enhance water usage efficiency, and reduce the need for manual intervention [5].

The proposed irrigation control system employs the Fuzzy method and the Nodemcu ESP8266 microcontroller platform. The Fuzzy method monitors the temperature and humidity of the hydroponic lettuce environment, ensuring optimal growth conditions [14]. Nodemcu ESP8266, a WiFi-enabled microcontroller platform, facilitates the use of sensors to monitor environmental conditions and control devices remotely via the internet. Leveraging the capabilities of the Nodemcu ESP8266, the automated irrigation system can operate efficiently and respond dynamically to environmental changes.

The system design incorporates optimal irrigation parameter settings, including irrigation duration and water volume delivered to the plants. Proper settings ensure that the plants receive adequate water without overwatering or underwatering [15]. These measures contribute to maintaining an ideal growth environment for hydroponic lettuce, enhancing both productivity and sustainability.

This study aims to design and implement an IoT-based automatic irrigation system for hydroponic lettuce cultivation, leveraging fuzzy logic to improve irrigation control [16]. The system also integrates cloud computing for remote monitoring, providing real-time updates to growers and enabling them to optimize water usage and crop growth.

This research seeks to evaluate the effectiveness of an IoT-based automatic irrigation system in improving hydroponic lettuce cultivation by enhancing resource efficiency, minimizing human intervention, and ensuring optimal growth conditions.

II. LITERATUE REVIEW

The application of IoT in agriculture, particularly in hydroponic systems, has been widely explored in recent years. Previous studies have highlighted various IoT-based irrigation systems that enhance water efficiency and improve crop productivity. To provide a clearer understanding, a comparative table summarizing these systems is presented in Table I.

TABLE I. Summarizing IoT Components

No	IoT Components	Irrigation Type	Key Features	Efficiency Gains
1	Soil moisture sensors, WiFi	Automated	Real-time monitoring of soil moisture	20% reduction in water usage
2	Temperature & humidity sensors	Manual-to-automated	Integration of climate control for optimal growth	25% increase in crop yield
3	pH & moisture sensors	Fully automated	Comprehensive environmental monitoring	30% reduction in labor costs

While these studies demonstrate the potential of IoT-based systems to improve efficiency, there are still some knowledge gaps, particularly in sensor calibration accuracy and the scalability of these systems. This research aims to address these gaps by developing a more precise IoT-based irrigation system that employs fuzzy logic for dynamic control, ensuring optimal irrigation while minimizing water wastage [17].

In addition, there are also several studies that have explored IoT-based systems for smart agriculture. A comparative analysis of several IoT-based irrigation systems is presented in Table II.

TABLE II. Comparative Analysis of IoT-Based Irrigation Systems

Author & Year	IoT Platform	Control Logic	Target Plant	Cloud Integration	Notable Features
Zhao & Wang (2022)	Arduino + WiFi	Threshold-based	Tomato	AWS IoT	Basic automation
Yudhanto et al. (2023)	Raspberry Pi	Manual override	Kale	Blynk	Manual feedback
Juanda (2020)	NodeMCU ESP8266	Rule-based	Lettuce	Thingspeak	Mobile app UI
This study	NodeMCU	Fuzzy Logic	Lettuce	Firebase	Adaptive control

Author & Year	**IoT Platform**	**Control Logic**	**Target Plant**	**Cloud Integration**	**Notable Features**
	ESP8266				

Previous systems often relied on static thresholds and lacked adaptability to dynamic environmental changes. Moreover, few systems addressed scalability and real-time integration with cloud services [18]. This study addresses these gaps by incorporating fuzzy logic for dynamic control and Firebase for scalable cloud storage and remote monitoring.

III. METHODS

The methodology for this research involves the integration of fuzzy logic with IoT technology to control irrigation based on environmental conditions. The fuzzy logic algorithm is implemented through the Nodemcu ESP8266 microcontroller platform, which is WiFi-enabled and allows for remote data collection and control [19].

In terms of cloud computing/storage, the system utilizes Google Cloud Platform (GCP) for remote monitoring [20]. This platform collects sensor data and allows growers to access real-time information on their hydroponic system via a website interface [21].

For system testing, the research involved conducting five test runs to ensure the reliability and accuracy of the system. Each test run simulated real-world environmental conditions to evaluate the system's response to changes in moisture levels [22]. The results from these tests confirmed the system's ability to automate irrigation effectively and respond to fluctuating moisture levels. This Methodology Serves as a Systematic Guide for Final Project Execution. The research methodology flowchart is illustrated in Fig. 1.

The research was conducted through six phases: requirements analysis, prototype design, sensor testing, IoT development, system testing, and evaluation.

A. *Needs Analysis*

1. *System Architecture*
   The system consists of NodeMCU ESP8266, a soil moisture sensor, temperature and humidity sensors (DHT11), relay module, water pump (DC motor), LCD display, and Firebase cloud storage. Communication occurs via Wi-Fi, enabling real-time updates
2. *Fuzzy Logic Control*
   The fuzzy logic controller takes two inputs—temperature and soil moisture—and outputs a water pump activation duration. The membership functions are defined as follows:
   - Temperature: Low (15-20°C), Medium (21-25°C), High (>25°C)
   - Moisture: Dry (0-40), Moderate (41-70), Wet (71-100)
   - Output: Irrigation duration (Short, Medium, Long)
3. *Sample Fuzzy Rule Set:*
   - If temperature is High and moisture is Dry, then irrigation is Long.
   - If temperature is Medium and moisture is Moderate, then irrigation is Medium.
   - If temperature is Low and moisture is Wet, then irrigation is Short.

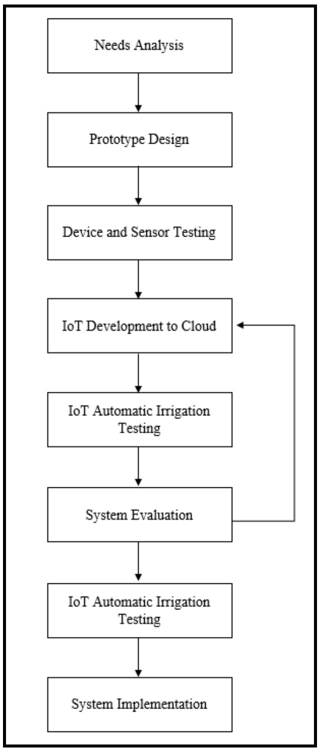


Fig. 1. Research Methodology Flowchart

B. *Prototype Design*

The Prototype Design stage involves the process of designing a prototype for the system based on the results of the first stage, conducted collaboratively with the system's users or owners. The system prototype design is described in Fig. 2.

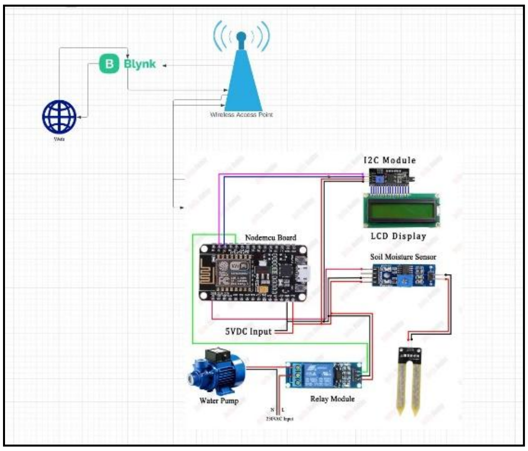
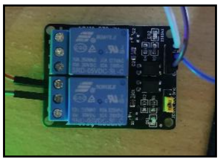
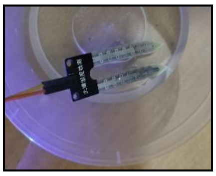
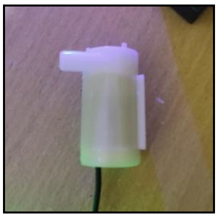
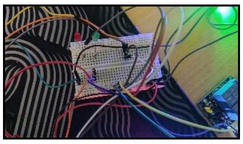


Fig. 2. Prototype Design

C. Testing of Devices and Sensors

This stage involves testing the devices and sensors that will be used. The purpose of this stage is to determine whether the devices and sensors can function stably before they are implemented. The devices used for testing are listed in Table III.

TABLE III. Testing Devices

No	Pictures	Tool Name
1		NodeMCU v3 / ESP8266
2		Relay
3		Humidity Sensor
4		DC Motors
5		Power Supply (can be replaced with 9V battery)
6		Breadboards
7		Jumper Cables
8		LCD Displays

D. IoT Development to Cloud

In this stage, the IoT technology is developed and implemented with programming code. This stage also involves designing interactions and developing the prototype for IoT to cloud integration, which will connect to the website.

E. Testing of IoT Automatic Irrigation

During this testing phase, the accuracy of the system is assessed both before and after the release of the IoT-based Water Quality Monitoring system.

F. System Evaluation

System evaluation is the final process to ensure that the developed system meets the needs of the users or system owners. This stage also verifies whether each sensor used is accurate in its measurements. If the system does not meet the requirements, it will be revised and improved in stages three and four. If the system is found to be satisfactory, it will proceed to the next phase.

G. System Usage

The final stage is the usage of the system. Once the system is deemed functional and has passed all tests, it is ready for operation and can be used by the system's users.

IV. RESULTS AND DISCUSSION

A. Design Result

After going through the stages of design, device testing, and development, the software was created to display and control humidity through a website-based system. This system functions to display humidity readings and control automatic irrigation. Below is the design result shown in Fig. 3. The model of the automatic system integration design was developed according to the design and hardware testing. Fig. 3 illustrates the design of the device, which consists of several components, each representing the tools used. The design results can be seen in Fig. 3.

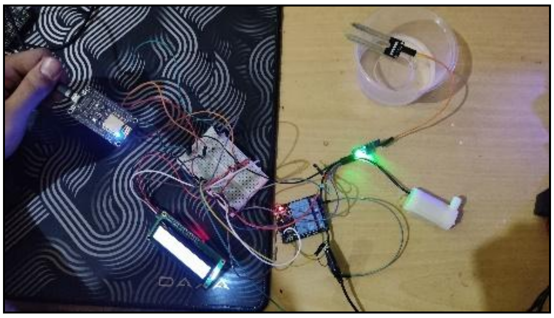


Fig. 3. Design Results

B. Testing of Devices with Software

This testing is conducted to determine whether the devices and system function correctly and as expected, producing data or outputs in line with the initial planning and design. The system testing begins with separate and sequential testing of both hardware and software components. The data obtained from the tests will serve as the basis for analysis to assess whether the system operates correctly, and will form the foundation for drawing conclusions and recommendations in the following chapters. The soil moisture results under dry conditions are shown in Fig. 4.

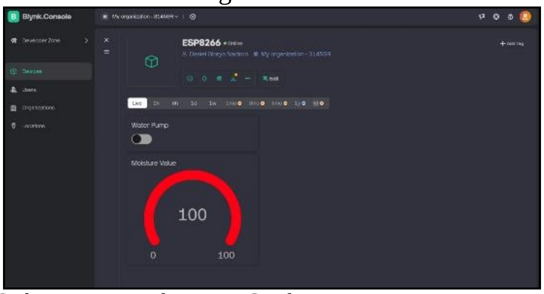


Fig. 4. Soil Moisture Results in Dry Condition

The moisture condition results under different scenarios are demonstrated in Fig. 5.

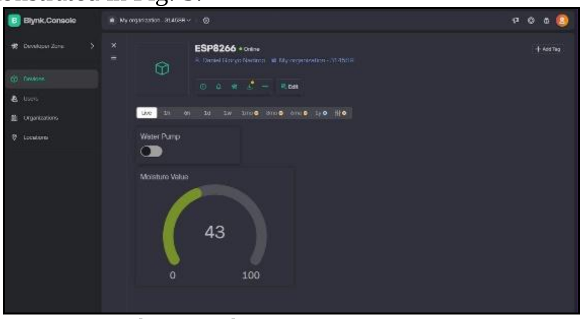


Fig. 5. Moisture Condition Results

From Fig. 4, it can be observed and concluded that when the reading shows a value of 100, it indicates that the soil moisture is dry. Based on this result, the user receives a notification to irrigate the hydroponic plants. After irrigation, if the reading shows a value below 80, it indicates that the soil moisture is now moist. The result of the moist medium can be seen in Fig. 5.

The system successfully automated irrigation based on real-time environmental input. Fig. 4 and Fig. 5 illustrate conditions under dry and moist states, respectively. The efficiency comparison between the tested methods is summarized in Table IV.

TABLE IV. Efficiency Comparison

Metric	Manual Watering	IoT-Based System
Average Water Use (L/day)	2.8	1.9
Plant Growth Rate	Moderate	High
Labor Hours/Week	4.5	1.0

The system's performance was evaluated by comparing IoT-based automated irrigation with manual watering. The results showed significant efficiency gains in terms of water usage and response time. The summary of the system's condition during testing is presented in Table V.

TABLE V. Summarizes Condition

Condition	IoT-based Irrigation	Manual Irrigation	Efficiency Gain
Dry Soil	Automated trigger	Manual check	50% faster response
Moist Soil	Automatic stop	Manual check	40% water saving

Apart from these improvements, a number of issues also came up during the testing phase. The calibration of the sensors continued to be a problem, particularly with moisture readings. There were also issues with connectivity, primarily regarding suspended data transfers between the cloud and the system. In addition, the IoT device's power consumption was a problem because the system needs to run 24/7.

Even with these hurdles, the system was able to diminish the amount of water used and the manual labor needed for irrigation when compared to the traditional processes. Moving forward, other developments will focus on ensuring the system is accurate with sensor data and reliable when it comes to consuming energy and monitoring system connections.

V. CONCLUSION

This research successfully developed and tested an IoT-based automatic irrigation system for hydroponic lettuce cultivation. The system demonstrated significant improvements in irrigation efficiency, water savings, and labor reduction. By integrating fuzzy logic and cloud computing, the system is able to provide real-time, remote monitoring and control, ensuring optimal growing conditions for hydroponic lettuce. Based on the design, testing, and implementation results, the author concludes that when the reading shows a value of 100, the soil moisture is dry, prompting the user to receive a notification for irrigation of the hydroponic plants. After irrigation, if the reading shows a value below 80, it indicates that the soil moisture is moist. When the moisture level is optimal, irrigation can be stopped.

Future work will focus on addressing the limitations identified during testing, including sensor calibration, connectivity, and power consumption. Additionally, the scalability of the system will be explored to ensure its applicability to larger hydroponic operations. The integration of IoT technology into hydroponic systems holds great potential for enhancing the sustainability and efficiency of modern agriculture.

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