Enhancing Hydroponic Farming Productivity Through IoT-Based Multi-Sensor Monitoring System

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Abstract: Hydroponic farming has gained prominence in modern agriculture owing to its inherent advantages in resource efficiency and crop yield. This research explores the integration of Internet of Things (IoT) technologies to further optimize hydroponic systems by monitoring and controlling crucial solution and environmental parameters. A novel IoT-based hydroponic monitoring system has been developed, featuring a comprehensive array of sensors including solution's temperature, acidity (pH), total dissolved solids (TDS) and electrical conductivity (EC), ambient temperature and humidity, and light intensity. This system leverages both WiFi and LoRaWAN technologies to enhance connectivity, ensuring reliable communication over extended ranges. This integration of communication protocols facilitates seamless data transmission and real-time control of hydroponic conditions. The proposed IoT-based system aims to provide growers with a comprehensive and user-friendly platform to monitor and adjust key parameters critical for plant growth, thereby maximizing the productivity and yield in hydroponic farming. The results of this study contribute valuable insights into the potential of IoT technologies to revolutionize precision agriculture and sustainable food production.

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1 INTRODUCTION

The agricultural sector plays a crucial role in numerous global economies, with traditional land-based farming remaining the primary source of food production. However, traditional agriculture confronts various challenges, including climate change, cultivation difficulties, and rising transportation costs. Essential elements like fertilizers, pesticides, and irrigation systems are pivotal for enhancing the quality of agricultural products. Yet their prices continue to escalate alongside operational expenses such as irrigation and machinery. Moreover, challenges persist due to extensive distances between markets and agricultural sites, inadequate transportation infrastructure, and volatile fuel prices. These hurdles serve as catalysts for innovation and creativity to address present agricultural dilemmas, particularly impacting small-scale farmers with limited financial means and capabilities. Escalating cultivation and transportation expenses threaten to erode profits and to burden farmers with debt, potentially discouraging them from continuing their farming practices. To optimize resource utilization and to mitigate the environmental impacts, soil-less farming techniques like hydroponics have gained considerable traction.

Hydroponic systems offer several advantages over the conventional farming methods, including resource efficiency, controlled environmental conditions, and reduced ecological footprint. By cultivating plants in nutrient-rich water solutions, hydroponics eliminates the need for soil, promoting faster growth with increased yields. Furthermore, technological advancements, such as LoRaWAN (long range wide area network) technology, facilitate remote monitoring for enhanced efficiency and effectiveness. LoRaWAN, recognized for its reliability and energy efficiency in long-distance wireless communication, enables real-time monitoring of various agricultural parameters like temperature, humidity, soil pH, and nutrient levels. This can empower farmers to make informed decisions promptly, adapting to evolving environmental conditions with greater precision and efficacy.

Recent years have witnessed a significant integration of sensors and actuators into hydroponic farming systems, enabling precise control and measurement of crucial environmental parameters for optimal plant growth. This integration has been emphasized

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by Niu et al. (Niu and Masabni, 2022), highlighting the importance of proper nutrition, conducive temperatures, and appropriate growing solutions for successful hydroponic farming. Several studies have focused on the synergy between IoT technology and hydroponic agriculture. For example, Fang et al. (Fang et al., 2014) developed a comprehensive system combining IoT technology with other monitoring tools to track environmental changes, whereas Bakhtar et al. (Bakhtar et al., 2018) engineered a hydroponic setup with sensors and remote control mechanisms to optimize spinach cultivation by monitoring humidity, temperature, and water levels. Their systems conduct real-time data analysis, triggering notifications for deviations from predefined parameters. Additionally, they explored IoT challenges and opportunities within hydroponic contexts, including sensor accuracy, data security, and operational costs.

Other researchers, such as Dutta et al. (Dutta et al., 2021) and Nguyen et al. (Nguyen et al., 2022), have investigated leveraging IoT for indoor plant cultivation and automated monitoring of lettuce plants, respectively. Furthermore, studies like those by Changmai et al. (Changmai et al., 2018) have applied IoT for efficient watering of lettuce plants while monitoring vital parameters. The technological advancements have reshaped agriculture significantly with data exchange playing a pivotal role in enabling IoT functionalities. Various communication technologies including Bluetooth, ZigBee, WiFi, GPRS, and LoRa have facilitated the establishment of robust sensor networks. Researchers like Muangprathub et al. (Muangprathub et al., 2019) and Deokar et al. (Deokar et al., 2021) have demonstrated the collection and transmission of crop and water data via wireless sensor networks, enabling comprehensive monitoring of crops through smartphones or web applications. Moreover, other studies, such as those by Benyezza et al. (Benyezza et al., 2021) and Dasgupta et al. (Dasgupta et al., 2020), have explored IoT applications in optimizing water and energy consumption in irrigation and predicting plant growth using AI, respectively. Additionally, researchers like Rajkumar et al. (Rajkumar et al., 2018) and Komal et al. (Komal and Bhardwaj, 2014) have developed IoT systems for enhancing energy efficiency and introducing robotic applications in agriculture. Similarly, Mishra et al. (Mishra and Jain, 2015) and Codeluppi et al. (Codeluppi et al., 2020) have utilized IoT technologies for automating nutrient delivery to plants and managing livestock efficiently. Furthermore, Wang et al. (Wang et al., 2021) have expedited recycling processes in factories using LoRaWAN technology.

The objective of this research paper is to present a novel IoT-based hydroponic monitoring system. This system is equipped with an extensive array of sensors, including those for solution temperature, acidity (pH), ambient temperature, humidity, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and light intensity. Leveraging both WiFi and LoRaWAN technologies, it aims to enhance connectivity, ensuring reliable communication over extended ranges. Through seamless integration of communication protocols, the system enables real-time data transmission and facilitates immediate adjustments to hydroponic conditions. The primary goal of this IoT-driven solution is to provide growers with a user-friendly platform for monitoring and adjusting key parameters critical for plant growth, ultimately maximizing productivity and yield in hydroponic farming operations.

1.1 Measured Parameters and Related Sensors

- **Total Dissolved Solids (TDS).** TDS level in a hydroponic solution serves as a crucial indicator of nutrient concentration. TDS represents the total quantity of dissolved minerals, salts, and nutrients in the water. A higher TDS generally corresponds to a greater nutrient concentration in the solution. Monitoring TDS is essential for ensuring that plants receive an adequate and balanced supply of nutrients, promoting healthy growth. Deviations from the optimal TDS range can lead to nutrient imbalances, affecting plant development. Consequently, maintaining the right TDS level is integral to achieving precise control over nutrient concentrations in hydroponic systems, fostering optimal conditions for plant nutrient uptake and overall growth.
- **Solution Acidity (pH).** The pH level in hydroponic nutrient solutions profoundly shapes plant growth by influencing nutrient availability and uptake. Maintaining the optimal pH range of 5.5 to 6.5 is crucial, ensuring nutrients are in a soluble form accessible to plants. Deviations lead to issues like deficiencies, toxicities, and compromised enzyme activity. pH impacts microbial activity, influencing nutrient cycling, and directly affects root health. Efficient nutrient uptake, enzyme functionality, and microbial support are all contingent on maintaining the right pH. Regular monitoring and adjustment of pH levels are imperative, fostering an environment conducive to balanced nutrient availability, optimal uptake efficiency, and overall robust plant development in hydroponic systems.

- **Electrical Conductivity (EC).** EC level in hydroponic solutions plays a pivotal role in influencing plant growth by serving as a reliable indicator of nutrient concentration. An optimal EC range is vital for ensuring plants receive an appropriate nutrient supply, fostering robust growth. Inadequate EC levels may lead to nutrient deficiencies, while excessively high levels can result in nutrient toxicity, both adversely affecting plant development. Maintaining a balanced EC is crucial to achieving optimal nutrient uptake and preventing nutrient imbalances. Additionally, there exists a dynamic relationship between EC and pH levels. Alterations in one parameter can impact the other, underscoring the importance of coordinated adjustments. Properly synchronized EC and pH levels are essential for creating a harmonious nutrient environment, promoting healthy plant growth, and mitigating potential nutrient-related challenges within hydroponic systems. Regular monitoring and precise management of both factors contribute to achieving optimal plant performance in hydroponic cultivation.
- **Solution Temperature.** The temperature of a hydroponic solution is pivotal for plant growth and performance. Optimal water temperature ensures efficient nutrient uptake, metabolic processes, and enzymatic activity. Maintaining the right temperature is particularly crucial to prevent issues such as oxygen depletion, root rot, and moss accumulation. Cold water may impede nutrient absorption and encourage moss growth, while excessively warm water can lead to reduced oxygen levels, promoting conditions conducive to root rot. Careful temperature regulation is essential for preventing these challenges, ensuring a well-balanced hydroponic environment that fosters nutrient absorption and discourages detrimental factors like root rot and moss accumulation, ultimately promoting robust plant growth.
- **Environment Temperature and Humidity.** The meticulous control of air temperature and humidity in hydroponic farms is indispensable for creating optimal growing conditions, particularly in the context of nutrient absorption and disease prevention. Precise humidity regulation holds immense significance, as it directly influences transpiration rates—the pivotal process through which plants absorb nutrients. Fluctuations in humidity levels can lead to irregular water uptake, potentially resulting in nutrient imbalances and hindered plant growth. Furthermore, the control of air temperature and humidity plays a vital role in disease prevention. Elevated humidity levels provide an ideal breeding ground for pathogens, increasing the susceptibility of plants to fungal diseases and other ailments. By diligently managing these environmental factors, hydroponic farmers can not only mitigate the risk of diseases but also optimize nutrient absorption. This strategic control contributes to the creation of an ideal environment that fosters vigorous plant growth, ensuring the maximization of crop yields in hydroponic cultivation.
- **Light Intensity.** Control over environmental light, or luminosity, is paramount in hydroponic farms to ensure optimal growing conditions for plants. Light is a primary factor driving photosynthesis, the process through which plants convert light energy into chemical energy, crucial for growth and development. Precise control of light intensity, duration, and spectrum enables growers to tailor conditions to the specific needs of different crops. Inconsistent or inadequate light can result in uneven growth, reduced yield, and poor quality crops. By carefully managing light levels, hydroponic farmers can optimize plant metabolism, nutrient absorption, and overall energy conversion. Additionally, controlling light exposure is essential for preventing issues like photo-inhibition, where excess light can harm plant tissues and hinder growth. Moreover, maintaining a consistent light schedule is crucial for regulating plant circadian rhythms, influencing processes such as flowering and fruiting. By fine-tuning luminosity, hydroponic growers can create an ideal environment that fosters robust plant growth, maximizes yield, and enhances the overall quality of crops in hydroponic systems.

In order to measure the above mentioned parameters, we have explored sensors from different manufacturers based on their cost, reliability, availability, and measurement range. Table 1 shows the list of the sensors used to developed our proposed monitoring system.

2 HARDWARE AND COMMUNICATION PROTOCOLS/INTERFACES

2.1 Sensors

The sensors used for our proposed system can be digital or analog. These simple sensors are connected to digital/analog pins of microcontoller to send and

Table 1: Detailed Specifications of Sensors.

No.	**Name of Sensor**	**Type**	**Input**	**Manufacturer**	**Parameter**	**Range**	**Cost**
1	DS18B20 Probe	Analog	$3-5.5$V	Dallas Semiconductor	Solution Temperature	$-55^\circ C - 125^\circ C$	USD 0.8
2	pH Sensor	Analog	$3.3-5.5$V	DFRobot	Acidity or Alkalinity	$5.5-7.5$	USD 40
3	TDS Sensor	Analog	$3.3-5$V	SeeedStudio	Dissolved Solids/Nutrient	$0-1000$ ppm	USD 14
4	BH1750 Sensor	Digital	$2.4-3.6$V	ROHM Semiconductors	Light Intensity	$0-65$K lux	USD 2
5	AHT10 Sensor	Analog	$3.3-5$V	Bosch	Temperature and Humidity	Temp: -40° C-80° C Humidity: $0-99\%$	USD 3
6	EC Sensor	Analog	$3-5$V	DFRobot	Solution's Electrical Conductivity	$0.07-50,000\ \mu$S/cm	USD 70

receive data. In order to facilitate connection of complex sensors, various hardware communication protocols (or Interfaces) can be used. For example, we have used AHT10 (high precision digital temperature and humidity) and BH1750 (light luminosity) sensors, which use I2C communication protocol for sending the data to the microcontoller. I2C stands for Inter-Integrated Circuit (I^2C), is the most versatile communication standard for connecting hundreds for sensors using a shared bus. There are other communication interfaces such as Serial Peripheral Interface (SPI) or Universal Asynchronous Receiver-Transmitter (UART), which can be used to connect the sensors. However, I2C provide clear advantage over other two considering the following:

- I2C does not require analog-to-digital conversion (ADC) to interface with the digital world. This digital communication simplifies the wiring and reduces the susceptibility to noise and interference, resulting in more accurate and reliable data transmission.
- I2C sensors use a simplified two-wire interface (SDA - Serial Data Line, and SCL - Serial Clock Line) for communication. I2C allows multiple sensors to be connected to the same bus, which means you can interface with several sensors using just a few pins of the microcontroller. Each sensor has a unique address, allowing the microcontroller to address and communicate with specific devices individually.
- I2C is a widely adopted standardized communication protocol with defined specifications, making it easier to integrate I2C sensors from various manufacturers into your projects without worrying about compatibility issues.

Even though I2C protocol emerges as the optimal choice for sensor connectivity, it's worth noting that the market offers a limited number of sensors with native I2C support. To overcome this limitation, we have developed an innovative I2C adapter prototype capable of converting any digital or analog sensor into an I2C enabled sensor, broadening the range of sensors that can utilize I2C protocol for communication. Readers can find more details about the prototype in the Section 5. In this work, we focus our attention on connecting the sensors using traditional digital/analog pins only. The integration of I2C adapter for each sensor will be explored in our future work.

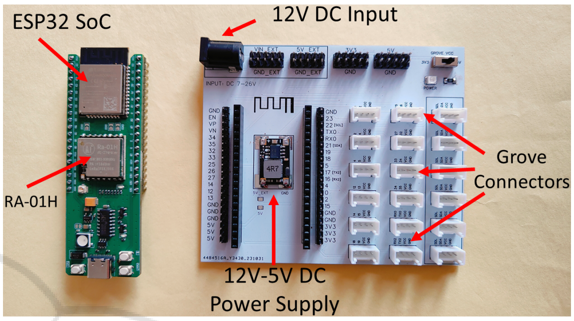

Figure 1: Microcontroller and Expansion Board.

2.2 Microcontroller and Expansion Board

In response to the limited availability of LoRaWAN microcontrollers in our region, we innovatively engineered a bespoke ESP32 + LoRaWAN-based microcontroller board. This board features additional 5V and ground pins, enabling seamless connection of multiple sensors simultaneously. Moreover, to streamline experimentation and mitigate the risk of loose connections, we devised an expansion board equipped with standard Grove connectors. Notably, this expansion board is designed with future-proofing in mind, capable of accommodating additional sensors through its expandable Grove connectors. Furthermore, for scenarios requiring enhanced power supply to the sensors, the expansion board includes 12V barrel connectors. Figure 1 illustrates both the developed microcontroller and expansion boards, showcasing their integrated design and versatility.

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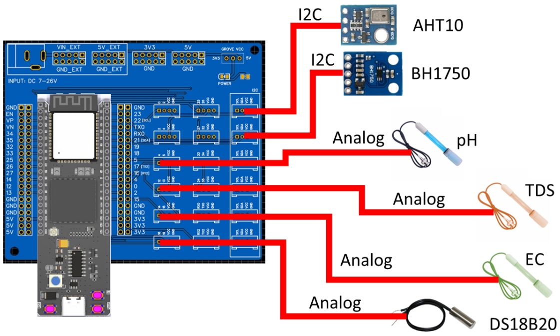

Figure 2: Peripheral Connection Diagram of an End-node.

2.3 Peripheral Connection Diagram

Figure 2 illustrates the comprehensive sensor-to-microcontroller board connections facilitated by the expansion board. Once the firmware is uploaded to the microcontroller board, the USB connection is disconnected, and power is subsequently provided via a 12V-5V DC power supply.

3 LOCAL AND WIDE AREA NETWORKING

The custom-designed microcontroller board incorporates ESP32-WROOM-32 (Espressif, 2024) and RA-01H (Ai-Thinker, 2024) SoCs, capable of supporting WiFi, Bluetooth, and LoRaWAN wireless technologies. Our project focuses on WiFi 802.11 (2.4 GHz Band) and LoRaWAN (868 MHz Band) in line with regional specifications. WiFi serves as a local area networking technology, enabling high-speed data transfer over short distances (approximately 100 meters). Conversely, LoRaWAN emerges as a long-range, low-power wireless solution tailored to meet the demands of IoT sensors and systems (Jouhari et al., 2023). With LoRaWAN capable of supporting thousands of end-nodes per gateway and offering coverage of up to 20 kilometers, it becomes an ideal choice for rural or remote agricultural IoT deployments where cellular or satellite connectivity may be impractical or unavailable.

Our system capitalizes on both WiFi and LoRaWAN technologies, enhancing reliability by enabling data transmission through either medium. Figure 3 illustrates the connectivity and data flow from end-nodes to the cloud server via WiFi access points and/or LoRaWAN gateways. In cases where end-nodes, such as End-Node 1 and 2, encounter limitations in data transmission via WiFi due to coverage issues, they seamlessly transition to LoRaWAN for dependable data transfer (Jouhari et al., 2023).

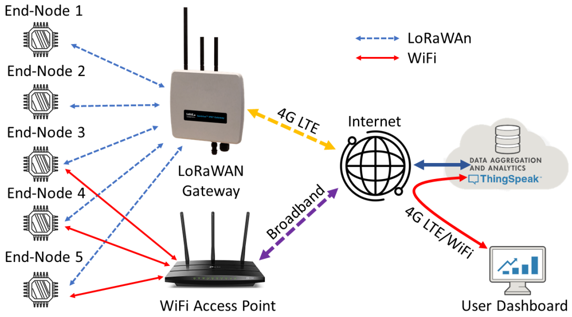

Figure 3: Network Connection for the IoT Setup.

For cloud services, we selected ThingSpeak as the provider due to its cost-effectiveness and provision of an integrated dashboard for real-time data collection and analytics (thingSpeak, 2024). This dashboard is accessible to end-users via a web browser or mobile application, facilitating remote monitoring and management from anywhere in the world.

4 DATA REPRESENTATION AND ANALYTICS

In this hydroponic system there are many nodes and these nodes can be equipped with LoRa transceivers. The node includes sensors to measure pH, temperature, humidity, light intensity, and gas concentration levels. Each node can also have a microcontroller to process data collected by sensors and then send it for wireless communication. In mesh communication, each node can be a sender and receiver of data. Each node is interconnected and forms its routing, where data can be delivered through intermediate nodes in the network.Figure 2 shows that in the hydroponic system that we built, with mesh communication, nodes can send their sensor data to the network server and send data to their neighboring nodes. These adjacent nodes, in turn, will convey further data until it reaches a node connected directly to gateways. With this relay mechanism, even nodes far from the gateway can communicate effectively. In addition, with mesh communication, if a node experiences an interruption, the network can reroute the data to an alternative path so that the information reaches the destination.

In this hydroponic system, data will be collected by sensors, packaged into LoRa packets, and sent to the LoRa gateway to be forwarded to The Things Network (TTN). TTN is a cloud-based LoRaWAN platform that manages and collects sensor data, ensuring its integrity and authenticity. TTN also offers an API

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to access stored data for further analysis. In this hydroponic system, sensor data sent via LoRa is displayed on the Node-RED dashboard. The dashboard connects to the TTN API to capture real-time sensor data and present it via graphs, charts, or visual representations so users can access this information on the web and mobile devices.

One of the big challenges in a hydroponic system is nutrient balance, therefore it is necessary to understand nutrient mixing. According to (Son et al., 2020) mixing nutrients can be done periodically as shown in Eqn. 1:

$$C_T EC_T = C_c EC_c + bUU = \frac{C_t EC_t - C_c EC_c}{b} \tag{1}$$

for EC calculating by Eqn. 2:

$$EC_{22} = \frac{EC_t}{1 + \alpha C(t - 22)} \tag{2}$$

where C_t is the maximum capacity that can be achieved by the solution in the tank, EC_t is the target electrical conductivity value dSm^{-1} to be achieved, C_c and EC_c are the current volume of nutrient-rich solution from the nutrient tank, U are the nutrients absorbed by the plant in the tank. b are empirical coefficients for EC conversion and salt concentration. According to (Jung et al., 2019), the b coefficient value that is suitable for hydroponics is $b = 9.819$, while the EC_t value that is considered suitable is in the range of $0.8 - 4.0\ dSm^{-1}$.

In order for the hydroponic system to operate efficiently some of the sensors we use in this system need to be calibrated beforehand in order to obtain accurate and reliable measurements, maintain sensor performance and to ensure the quality of the results. For the TDS grove sensor used in this system, we first convert the analog reading into voltage using Eqn 3:

$$Voltage = sensorValue \times \frac{5.0}{1024.0} \tag{3}$$

where *Voltage* is a variable that will store the voltage value calculated from sensor readings and *sensorValue* is a variable that stores the analog reading obtained from the Grove TDS sensor. For TDS sensor, we need to calibrate first using Eqn. 4.

$$\begin{aligned} tdsValue = &(133.42/Voltage^3 - 255.86 \times Voltage^2 \\ &+ 857.39 \times Voltage) \times 0.5 \end{aligned} \tag{4}$$

and for pH, we need to calculate using Eqn. 5.

$$ph\_act = -5.70 \times volt + calibration\_value \tag{5}$$

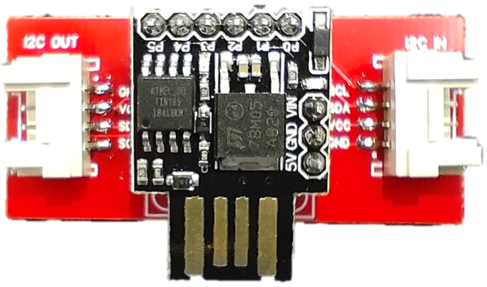

Figure 4: I2C Adapter.

5 FUTURE RESEARCH DIRECTIONS

To expedite programming and simplify sensor replacements, we embarked on developing an I2C adapter board facilitating communication between any digital/analog sensor and the primary microcontroller via the I2C protocol. For *N* sensors, *N* I2C adapters are employed, each endowed with a unique, programmable I2C address for communication. Essentially, the I2C adapter board operates as a low-power microcontroller, gathering digital/analog data from a sensor and transmitting it to the primary microcontroller via the I2C protocol. Figure 4 showcases the prototype of our I2C adapter board, employing an inexpensive ($1) ATTINY85 microcontroller. In future iterations, our goal is to minimize the size and power consumption of this adapter board to seamlessly integrate it with hydroponic sensors.

Apart from developing I2C adapter, we plan to utilize the Bluetooth connectivity option available in the ESP32 SoC to create a multi-hop mesh network. This will allow end-nodes which are not in range of both WiFi router and LoRaWAN gateway to relay data via neighboring end-nodes. This will further increase the coverage range for the end-nodes.

6 CONCLUSIONS

The surge in interest towards hydroponics and aeroponics, driven by limited fertile soil availability, underscores the need for precise monitoring of environmental conditions. To address this, we introduce an IoT-based multi-sensor monitoring system tailored for hydroponic agriculture. Distinguished from existing solutions, our system boasts a broader parameter measurement range and combines LoRaWAN and WiFi technologies for extended data transmission in WiFi/cellular challenged areas. Additionally, our innovative I2C sensor adapter simplifies sensor commu-

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nication and replacement, enhancing system flexibility. Future developments will focus on refining the I2C sensor adapter design and integrating Bluetooth mesh networking for further system optimization.

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