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Design and Implementation of an Automated Indoor Hydroponic Farming System based on the Internet of Things

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Abstract: Urban farming has been growing in popularity to help secure food needs in urban areas. Hydroponic is one of the methods to grow crops without soil media being an option for urban farming. However, hydroponic farming has its challenges as farmers must carefully monitor the environmental conditions of the plants regularly and adjust the nutrient solution and water circulation based on the environmental conditions. This paper describes designing and implementing an IoT-enabled hydroponic farming system to monitor the environmental condition of plants and control the nutrient supply plants. Our system is built from sensors, actuators, a micro-controller unit (Arduino), and a single-board computer (Raspberry pi) attached to the hydroponic system. The system can monitor the environmental condition of hydroponics through sensors such as temperature, humidity, pH sensors, and Total Dissolve Solid (TDS) sensors and control water pumps to circulate the nutrients to the plant. The Raspberry pi acts as a Message Queuing Telemetry Transport (MQTT) broker for distributing the data from sensors to subscribers. It also controls the nutrient pump to adjust nutrient solution. We use Node-RED installed in the Raspberry pi to build and connect the system to hardware devices. Users can monitor the environmental condition of plants in hydroponics through a web browser on their smartphone and laptop. This IoT-based indoor hydroponic system can automate the delivery of nutrients and water to plants, ensuring they receive the optimal amount at the right time.

Keywords: Internet of Things, Hydroponic, MQTT, Node-Red, Sensors

1. INTRODUCTION

Urban farming is growing crops in urban areas utilizing small vacant land and space, such as house yards and indoor spaces. The yields of this cultivation are often consumed locally or distributed to the nearest local supermarket. Moreover, urban farming grows plants that are often consumed daily, such as vegetables, mushrooms, fruits, tubers, medicinal plants, or ornamental plants. Today, urban farming with hydroponics is gaining attention. Hydroponic is a solution to produce high-quality agricultural products sustainably with a high quantity plant. Hydroponic is a method of cultivating plants without soil by utilizing water as a growth medium. The roots of the plants are submerged in nutrient-rich water that is constantly cycled to provide a steady water supply and nutrients.

The advantage of hydroponic farming is the more efficient use of resources because it uses less water than traditional soil-based farming, as water can be recirculated and reused. Additionally, plants can be grown in small spaces and vertical arrangements, maximizing available space. Regarding environmental impact, hydroponic farming does not require using pesticides, herbicides, or other chemicals that can negatively impact the environment. Moreover, with a hydroponic system, plants grow relatively quickly and result in higher yields with consistent quality and flavor as plants have access to a constant supply of nutrients and water, and the growing conditions can be precisely controlled. There are several studies stating the benefits of hydroponics. Reference [1] describes the benefits and types of plant cultivation using hydroponics. It concludes that planting using hydroponics can improve crop quality. Reference [2] explains the use of hydroponics for growing strawberries. This soilless farming is a sustainable agriculture practice. It is a viable alternative to soil farming to achieve a world free of hunger by 2030, an agenda for sustainable development [3]. However, hydroponics farming also has challenges, such as the need for specialized equipment and the initial cost of setting up a hydroponics system. Traditional hydroponics farming has often been constrained by the need for constant monitoring and manual intervention to maintain optimal environmental conditions for plant growth. For example, the nutrient solution must be carefully monitored and adjusted to ensure the plants receive the right balance of nutrients.

This paper proposed the adoption of the Internet of Things (IoT) technology to address certain challenges of traditional hydroponics farming, and it has the potential to revolutionize our approach to food production.

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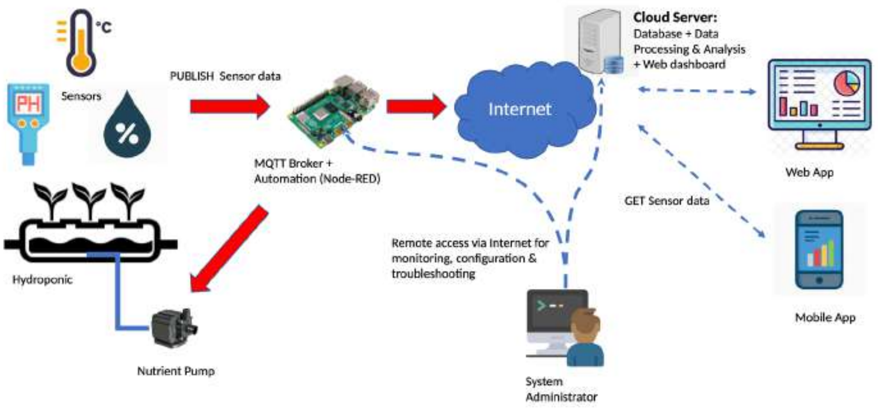


Figure 1. System Architecture

2. Related Works

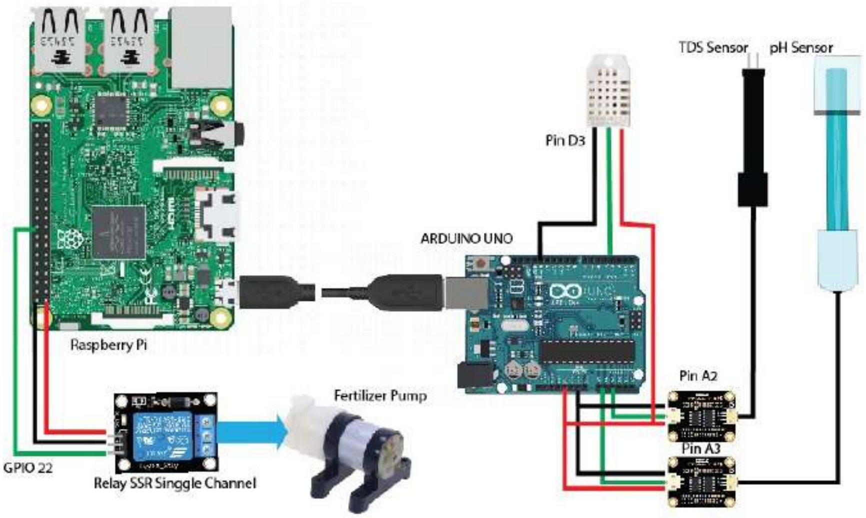
Currently, farming using IoT technology in controlling and monitoring crops, commonly referred to as smart farming, is getting attention for precision agriculture to improve yields. A lot of research on hydroponic automation has been done. Reference [4] reviews the use of different kinds of hydroponics and supporting IoT technology that can increase food production. The use of hydroponic systems in decentralized food production for small and medium scale impacts the local economy, which can create new jobs or profitable business activities. Reference [5] designed and implemented a system to monitor strawberry growth in hydroponics and determine strawberry harvest time using IoT-Edge, artificial intelligence (AI), and cloud technology. Reference [6] proposed a system for automating the control and management of tropical hydroponic cultivation. The system controls water level, humidity, and temperature and sends data sensor status to the Android mobile application. Reference [7] conducts a literature review on plant cultivation techniques using hydroponics and proposes an intelligent hydroponic system for saffron cultivation utilizing IoT and renewable energy sources. Reference [8] [9] proposed an IoT-based hydroponic system using solar panels. The author in [8] proposed a system that can determine a suitable duty cycle of the system to determine the efficient use of the number of solar panels. On the other hand, the author in [9] developed a smart power plant unit applied to the proposed IoT system to detect voltage and current stream and perform an action to switch power between the solar panel and conventional electrical power. References [10] [11] [12] [13] proposed IoT-enabled monitoring and controlling system for the greenhouse. Reference [12] discusses the development of an IoT-enabled temperature monitoring and control system for a greenhouse. They use a Petri net model to monitor the temperature and determine a suitable temperature reference to be used as a reference in temperature regulation in the greenhouse. Reference [13] proposes an IoT-driven approach for optimizing greenhouse water supplementation while ensuring energy efficiency. Reference [14] developed an IoT-based monitoring and controlling system for hydroponic greenhouse. The system monitors water quality, temperature, and humidity to ensure the crop grows optimally in the greenhouse. Reference [15] has simulated a hydroponic automation system with a clustered-based and multihop-based Wireless sensor network (WSN) and compared the performance between the two WSN models using the OMNET Simulator. Performance evaluation shows that Multihop-based WSN has increased latency and energy consumption as the number of nodes grows while cluster-based WSN remains constant. Reference [16] designed an IoT-based monitoring system for hydroponic farming's environmental and nutrient solution parameters. The system performs well during the growth of lettuce in a Nutrient Film Technique (NFT) hydroponic system. Reference [17] discusses the implementation of IoT in the NFT hydroponic system for lettuce cultivation. The system utilizes sensors to measure temperature, water level, and pH, all connected to an Arduino for data collection, while a Raspberry Pi is used for data storage. Remarkably, the system achieves a significant reduction of 91.6% in electricity consumption. Reference [18] aims to overcome the problem of increasing world food needs using an IoT-based automated hydroponic system. The hydroponic system uses the NFT technique with various sensors, including temperature, humidity, pH, water content, and nutrient levels sensors connected to the PCB and Raspberry Pi 3 as an Message Queuing telemetry transport (MQTT) server. The system can be monitored and controlled through Node-Red and the Web GUI.

Reference [19] aims to develop a hydroponic system

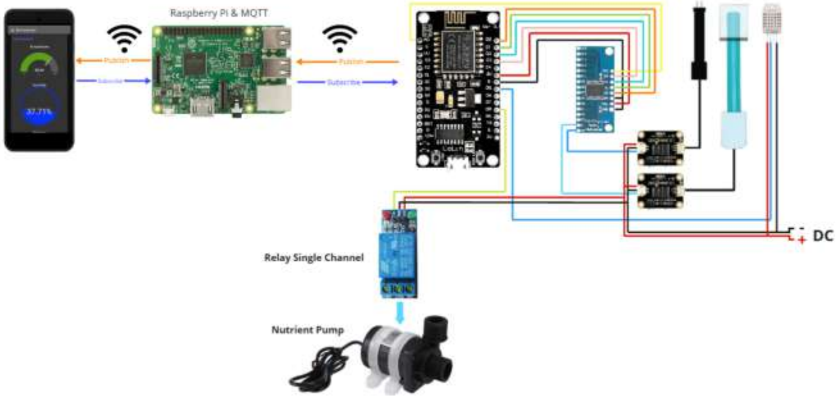
TABLE I. Comparison of Existing Solution

Ref.	Contribution	Sensor Parameter	Drawbacks
[4]	A comprehensive overview of the potential of hydroponics	Temperature, Humidity, pH	Lack of discussion on the IoT for hydroponics
[5]	IoT-Edge-AI-Cloud concepts to monitor strawberry hydroponic	pH, DO, TDS, Ultraviolet, Temperature, Humidity, CO2	Complex and expensive
[6]	Utilizes wireless sensor networks and data fusion techniques to streamline information exchange and improve control efficiency	water level, humidity, and temperature	No discussion on how the data is stored and how the communication between the sensor and the web server.
[7]	A comparative analysis of six hydroponic methods and focuses on researching saffron growth factors	Temperature, pH, Moisture	Not implemented yet
[8]	Integration of solar panel applications and IoT to lower the installation cost of solar panels in smart hydroponic farms.	transpiration leaf	Limited focus on Power consumption. Lack of discussion on how IoT improve the lettuce cultivation
[9]	An automation system for the hydroponics system and a smart solar power plant unit.	light intensity, voltage, electrical current, and solar panel output	Limited focus on Power consumption, No discussion on cultivated plant.
[10]	Systematic review of IoT-based greenhouse applications, sensors/devices, and communication protocols.	Soil Moisture, pH, Airflow, humidity, Accoustc, GPS, CO2	Lack of discussion on the practical challenges.
[11]	Reviews the existing greenhouse cultivation techniques and the latest advancements in IoT technologies for smart greenhouse farming	The authors do not proposed specific sensors	Lack of discussion on how IoT affect the plant growth
[12]	Utilizes a Petri Nets (PN) model for greenhouse environment monitoring.	Temperature	Limited focus on temperature control.
[13]	Proposes an optimal greenhouse water supplement mechanism that focuses on efficient energy consumption.	Water, soil moisture	The system was run in an experimental environment in the lab instead of a real greenhouse.
[14]	Intelligent and low-cost IoT-based control and monitoring system designed for hydroponic greenhouses.	Temperature, pH, water Electrical Conductivity (EC) and Dissolved Oxygen (DO)	No discussion on the data analysis and decision-making processes based on the collected sensor data.
[15]	Evaluates the performance of an automated hydroponic system using cluster-based wireless sensor networks in comparison with a multihop-based system.	Temperature, humidity, EC, and pH	Simulation-based and focuses on simulation results, without extensively discussing the practical implementation challenges
[16]	Focuses on designing and implementing an IoT-based automated monitoring system for hydroponic farming	Humidity, temperature, light intensity, pH, and EC	Lack of discussion on how IoT improve the lettuce cultivation.
[17]	Introduces the NFT-I hydroponic system	temperature, water level, and pH	Lack of discussion on how IoT improve the lettuce cultivation. No discussion on how data is stored and accessed
[18]	Design and implementation of an automated smart hydroponics system using the IoT	pH, Humidity, temperature, lighting	Lack of discussion on how IoT improve the lettuce cultivation. No discussion on how data is stored and accessed.
[19]	Propose a pH sensor that is designed to automatically detect and rectify imbalances in the nutrient solution's pH levels through calibration.	pH	lack of evaluation of crop performance and outcomes achieved with the smart system.
[20]	IoT-based automatic water level and EC monitoring system designed for the NFT	water level, EC	Lack of discussion on how the data is stored, the type of database used in the web server
[21]	Improvement of [14] by adding a fuzzy inference engine determines plant irrigation duration	Temperature, pH, EC and DO	No discussion on the data analysis and decision-making processes based on the collected sensor data.

with automatic pH calibration. The system uses a pH sensor and a series of micro-pumps to dispense various liquid solutions sequentially to maintain the sensor's calibration and collect water samples from the conduit containing the nutrient solution. The control algorithm aims to detect the presence of carbonate or bicarbonate in the nutrient solution, which determines the pH value. This system is visualized through a web portal. The results showed that this system was successful in maintaining hydroponic pH levels. Reference [20] aims to build an IoT-based hydroponic system that automatically adjusts water and water conductivity levels. The system built uses the HC-SR-4 sensor (to measure the water level), the EC sensor (to measure the conductivity level of the water, the higher the conductivity level, the more fertilizer is in the system), the DHT11 sensor (to measure the ambient temperature and humidity surrounding the system.), and water pumps (mounted on water tanks, nutrient tanks, and final water tanks). Reference [21] implements iPONICS, an IoT system to control water quality (temperature, dissolved oxygen (DO), electrical conductivity (EC), and pH) and monitor the temperature and humidity of the air in the greenhouse. The system will warn users when the water quality, temperature, or humidity exceeds a predetermined limit. The system



(a) Small-scale IoT-enabled Hydroponic System



(b) Medium-scale IoT-enabled Hydroponic System

Figure 2. System Hardware Design

will also provide information about the state of the system, which has been continuously updated for some time. The system obtained also experienced a possible error of 0.93% in sensor readings and 0.1% in data transmission.

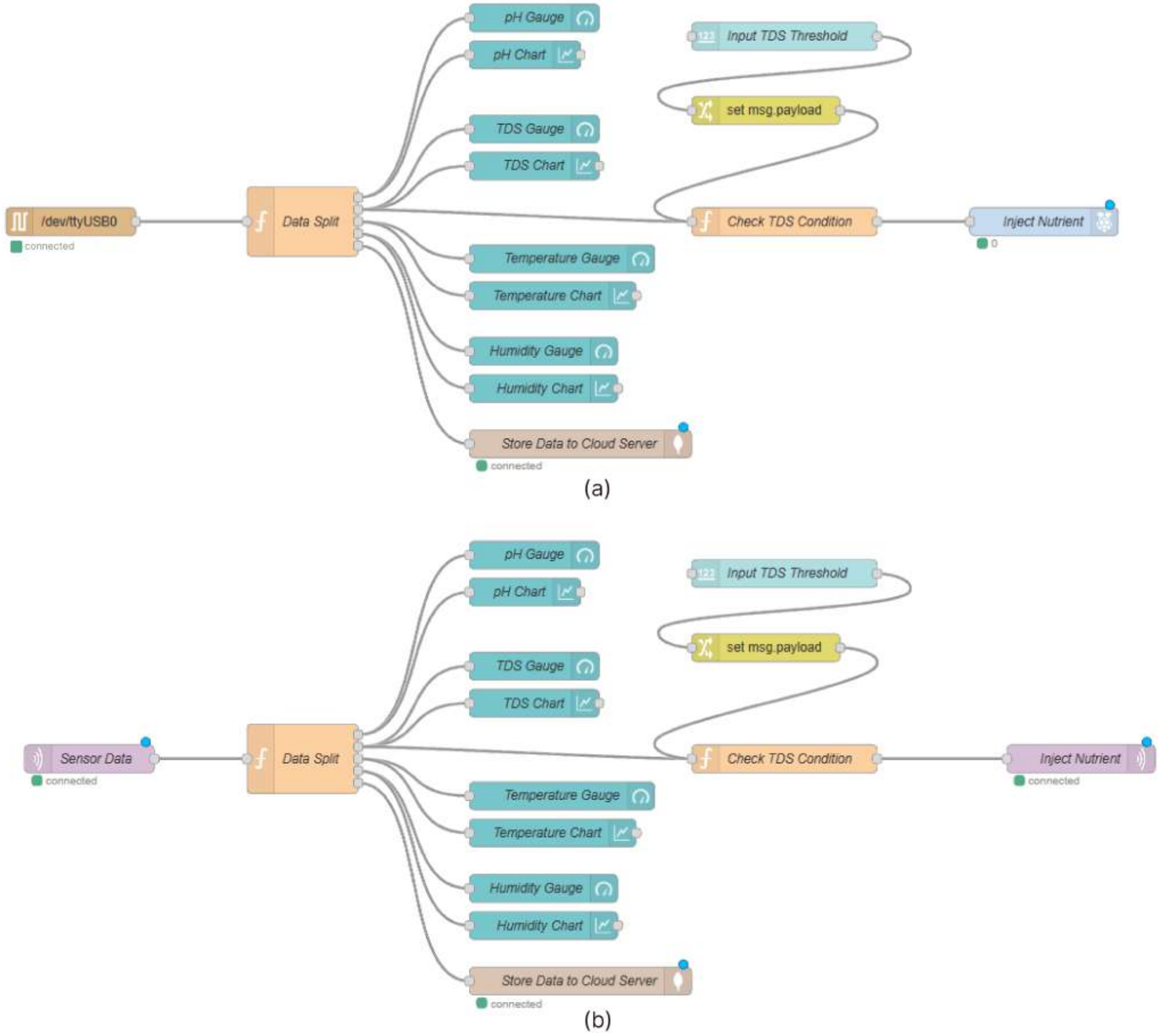
This paper proposes an IoT system that can work in small-scale and medium-scale indoor hydroponic systems. A small-scale hydroponic system is intended for use in limited areas, such as homes or apartments, while a medium-scale hydroponic system is intended for use when multiple sensor nodes exist, often installed in vast indoor or greenhouse facilities.

3. SYSTEM DESIGN

This IoT-based hydroponic system comprises five main components, i.e., sensor node, actuators, controller, MQTT broker, and cloud server, as shown in Figure 1. They are connected and communicate through the MQTT broker. MongoDB, a NoSQL database, is configured on the cloud server to store sensor data transmitted by the MQTT broker over the internet. The stored sensor data in MongoDB can be processed and analyzed to produce valuable information and for future reference. Accessing the sensor data is possible via the cloud server at http://smartfarm.unhas.ac.id.

A. System Hardware

Sensor Node consists of three sensors, including temperature, humidity (DHT11), power of hydrogen (pH), and total dissolved solids (TDS) sensors. The DHT11 is a digital sensor for measuring the air temperature and humidity in hydroponics systems. The pH sensor measures water's acidity or alkalinity. The value ranges from 0 to 14, with seven being Neutral. When the pH value is below 7, the water becomes more acidic. Otherwise, it becomes more alkaline. All plants have varying optimum pH levels, but generally, the optimum pH level for plants is between



(a)

(b)

Figure 3. Node-Red Flow Diagram

5.5 and 6.5. Furthermore, the TDS sensor measures the concentration of dissolved solids in the nutrient solution, which gives a reading in parts per million (ppm). The system feeds the plant based on the TDS level. TDS sensor measures the TDS level of the nutrient solution in real-time. Based on the measured TDS level, the system can adjust the nutrient solution to maintain a consistent TDS level within the desired range. The TDS level can vary depending on the type of plants being grown, the growth stage of the plants, and other factors. When the TDS sensor detects that the nutrient solution has fallen below the desired TDS level, the nutrient pump, as an actuator, can be activated to add more nutrients to the solution. Similarly, if the TDS level is too high, the nutrient pump can be adjusted to reduce the amount of nutrients added to the solution.

Figure 2 shows the system hardware consisting of a micro-controller unit (MCU), i.e., Arduino Uno, single-board computer (SBC), i.e., Raspberry pi 4, pH sensor, TDS sensor, DHT11 (temperature and humidity) sensor, and nutrient pump as an actuator. Details of technical specifications and power consumption of each component in operating mode can be seen in Table II. We propose a system that can be implemented in small-scale and medium-scale hydroponic systems. Figure 2a shows the hardware design for the small-scale hydroponic system where the Raspberry Pi is connected to the sensors on the Arduino via the serial port. This Raspberry pi is also connected to the relay to drive the nutrient pump through the digital pin of

TABLE II. Technical specifications of components and power consumption during operating mode

Components	Specification	Power Consumption
Single-Board Computer	Raspberry pi 4 Model, 2GB RAM	4 W
Micro-controller	Arduino UNO: ATmega328P / NodeMCU ESP8266	0.9 W
TDS Sensor	Gravity Analog TDS Sensor	0.6 W
pH Sensor	Gravity Analog pH Sensor	0.5 W
Temperature and Humidity Sensor	DHT11	0.8 W
Nutrient Pump	Mini Water Pump	0.5 W
Relay Module	1 Channel Relay Module	0.5 W
Submersible water pump	AMARA P-5200	50 W
Light (6 units)	TL LED 004 Super White	18 W

the Raspberry pi. Moreover, Figure 2b shows the hardware design for the medium-scale hydroponic system where communication between multiple sensor nodes (publishers) and the MQTT broker requires wireless connectivity. We use NodeMCU ESP8266, a small MCU with an integrated Wi-Fi module attached to Arduino, to establish wireless connectivity between the sensor node and the MQTT broker.

B. MQTT Broker

MQTT [22] is a lightweight and efficient messaging protocol suitable for IoT networks. The lightweight characteristics and low overhead of the MQTT protocol architecture guarantee seamless data transfer with minimal bandwidth usage and decrease the burden on the CPU and RAM. It is a publish/subscribe communication protocol implemented in Raspberry pi. For the medium-scale IoT-enabled hydroponic system, the Raspberry pi acts as an MQTT broker, receives the data from sensors as a publisher, and delivers them to subscribers who subscribe to that specific data. The advantages of applying an MQTT broker in medium-scale IoT networks are as follows:

- The MQTT broker can manage the data flow between devices and applications, reducing network congestion and improving the network's reliability.
- MQTT works well with low-power devices, such as battery-operated sensors. By using an MQTT broker, low-power IoT devices can communicate with each other without consuming excessive network resources.
- MQTT enables the communication between IoT devices and applications with intermittent network connectivity. When a device is offline, the MQTT broker will queue messages until it is back online and receive them.

Using MQTT, farmers can monitor the environmental condition of hydroponics by subscribing to a specific topic using the web browser on a PC or smartphone. The MQTT provides three levels of quality of service (QoS) as follows:

- QoS 0 (At most once) provides the lowest level of reliability. In QoS 0, messages are delivered once, but there is no guarantee of delivery. The sender publishes a message to the broker, and the broker delivers it to the connected subscribers.
- QoS 1 (At least once) ensures that messages are delivered at least once, but there might be duplicates. When a publisher sends a message at QoS 1, it will be acknowledged by the broker. If the broker receives the message, it returns an acknowledgment to the publisher. If the publisher does not receive the acknowledgment, it re-sends the message. After receiving the message from a publisher, the broker forwards it to the subscribers. If a subscriber is not currently connected, the broker will hold the message until the subscriber reconnects.
- QoS 2 (Exactly once): QoS 2 guarantees messages are delivered exactly once. It provides the highest level of reliability but also introduces more overhead in terms of processing and network traffic. QoS 2 involves a four-step handshake process between the publisher, the broker, and the subscriber to ensure message delivery and de-duplication. This ensures that each message is delivered only once, regardless of network interruptions or failures.

The proposed system applied MQTT QoS level 0 to minimize the network and processing overhead, especially when implementing an MQTT broker for a medium-scale hydroponic system. It is important to consider the scalability and performance of the broker to ensure that it can tackle the increased volume of data and the number of connected devices. Besides the MQTT broker, Raspberry pi also acts as a controller to drive the actuator (nutrient pump) based on the TDS level obtained from the TDS sensor. To add IoT functionality, node-RED [23] is used, and it runs on Raspberry pi.

C. Node-Red

The Node-RED [23] is used to draw the workflow of the IoT scenario. It is a web-based visualization tool for creating IoT scenarios by connecting IoT devices and services. The Node-RED runs on Raspberry pi and is secured with user authentication to access and modify the flow diagram to prevent malicious access. Additionally, only selected ports required for application usage are opened, while the rest are closed to enhance security.

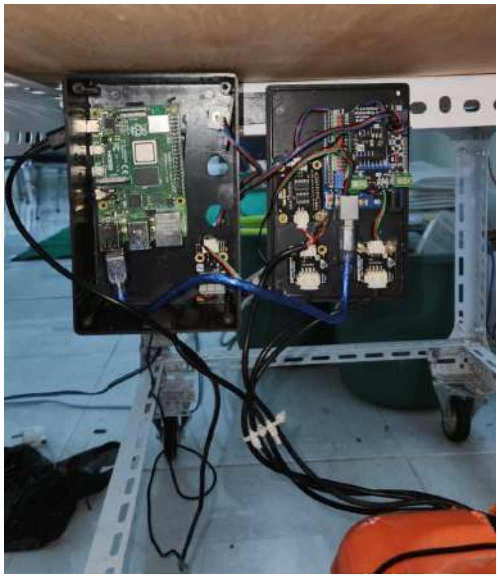


Figure 4. Sensor Node

There are two flow diagrams in our IoT scenarios. Figures 3a and 3b show the node-red flow diagram for small-scale and medium-scale IoT scenarios, respectively. The difference in the diagrams of these two scenarios is only the communication method between the sensor nodes and Raspberry pi as a broker. In the medium-scale scenario, the sensor node sends the sensor data to Raspberry pi (MQTT broker) through a wireless network. In contrast, the small-scale scenario does not use wireless communication, instead, the sensor node is connected directly to Raspberry pi through a serial port. Each flow diagram consists of two functions, i.e., Split Data and TDS Condition function. In the Split function node, the data from sensors are split into four data sensors, as shown in listing code 1. The gauge node is connected to the Split function node to display the numerical data from the connected sensor in real-time so that users can monitor the environmental condition of hydroponic through a browser on a PC/laptop or smartphone. For medium-scale IoT scenarios, the sensors publish the data to the MQTT broker, and the user can subscribe to specific data to obtain information regarding the environmental condition of hydroponics in real-time. Moreover, the TDS condition function node evaluates the status of the TDS value, as in listing code 2. When the TDS value is below the predetermined value (500 ppm), indicating plants need additional nutrients, the system activates the nutrient pump to inject and circulate the nutrients to the plant.

```
data = msg.payload
dataSplit = data.split("|")
result = [
            {payload:dataSplit[0]},
            {payload:dataSplit[1]},
            {payload:dataSplit[2]},
            {payload:dataSplit[3]}
         ]
return result
```

Listing 1. Split Data Function

```
var threshold = msg.topic
var tdsSensor =  parseInt(msg.payload)

var currThr = context.get('threshold') || 1000
var currTds = context.get('tds') || 1000


if(threshold){
    context.set('threshold', threshold)
}

if(tdsSensor){
    context.set('tds', tdsSensor)
}


if(currTds < currThr)
{
    return {payload:1}
}else
{
    return {payload:0}
}
```

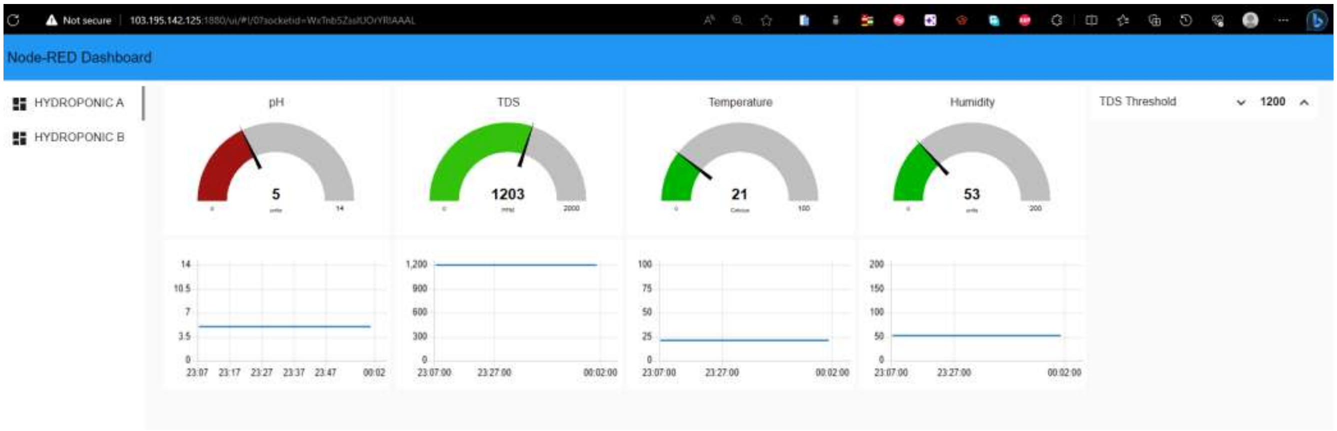
Listing 2. TDS condition check

4. Result and Discussion

We have built an IoT-enabled indoor hydroponic farming system, as shown in Figures 4 and 5. It consists of three shelves, and each shelf is supplied with water, nutrients and artificial lighting. At the bottom of the rack is a container containing water and nutrients, which will be distributed to each shelf using a pump. The hydroponic system is powered with electricity from our laboratory building, which is backed up with an uninterrupted power supply (UPS) to maintain the electricity supply to the hydroponics during power outages. Regarding power requirements, our indoor hydroponic system requires 165 watts of power to run all components, as shown in Table II. Moreover, as shown in Figure 6, our system provides a web dashboard for monitoring the environmental conditions of hydroponics, including pH, TDS, temperature, and humidity. The web dashboard provides real-time information about environmental conditions.

We have grown spinach in hydroponics and collected data on hydroponic environmental conditions. Figures 7 and 8 show the average pH and nutrient concentration in the container water on a daily basis. As shown in Figure 7, the pH of the water ranged from 5 to 6 every day. The optimal pH range for growing spinach in hydroponics is between 5.5 and 7.0. Spinach plants can tolerate slightly acidic to slightly alkaline conditions but tend to grow best in a slightly acidic environment. When the pH of the nutrient solution is too high or low, it can lead to nutrient deficiencies or toxicities, which can cause stunted growth and poor yields. Regularly monitoring and adjusting the pH

Figure 5. IoT-enabled Indoor Hydroponics System



TDS Threshold 1200

Figure 6. Web Dashboard for Monitoring

of the nutrient solution is crucial to achieve optimal plant growth and health. Figure 7 shows the average pH level of spinach grown in our hydroponics. Meanwhile, the nutrient concentration can be kept between 500 and 600 ppm, as shown in Figure 8. The optimal TDS range for growing spinach in indoor hydroponics is between 500 and 1500 ppm, depending on various factors, including the specific nutrient solution used, the growing environment, and the stage of plant growth. TDS measures the concentration of dissolved solids in the nutrient solution, including minerals and other nutrients that the plants need to grow. If the TDS is too high, it can lead to nutrient toxicity, harming the plants. On the other hand, if the TDS is too low, it can cause nutrient deficiencies, affecting plant growth and yields. It is important to regularly monitor and adjust the TDS level to ensure optimal plant growth and health.

The implementation of an IoT-enabled hydroponic farming system holds significant implications for the future of urban agriculture. This system allows for precise monitoring and control of the environmental conditions within hydroponic setups, enhancing crop yields and resource efficiency. The utilization of sensors, MCU, and SBC, such as the Arduino and Raspberry pi, facilitate real-time data collection and distribution. Our proposed system also reduces the need for manual intervention, making urban farming more accessible and manageable. Therefore, our proposed system offers a promising step toward sustainable and technology-enhanced urban agriculture.

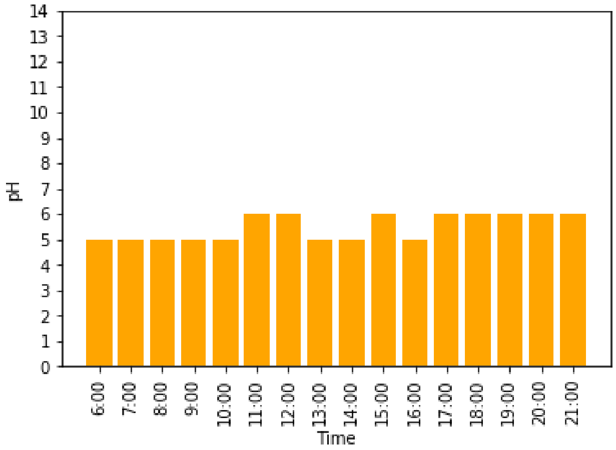


Figure 7. Average pH Level

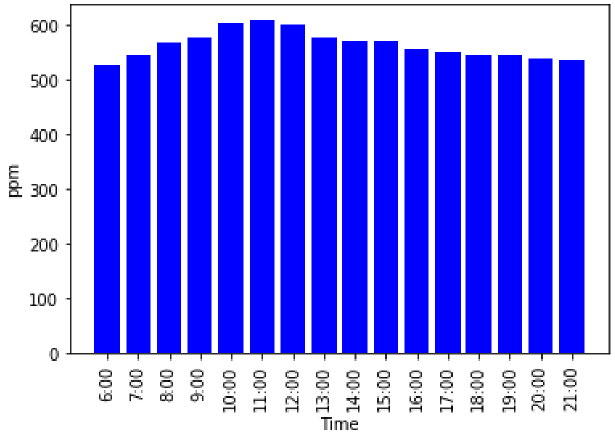


Figure 8. Average TDS Level

5. Conclusion and Future Direction

This paper presents designing and implementing an IoT-enabled Hydroponic farming system that can address the challenges urban farmers face in growing crops without soil. By monitoring the plants' environmental conditions and controlling the nutrient supply, this system can ensure optimal growth by automating the delivery of water and nutrients to the plants. The hydroponic system is connected to various components, including sensors, actuators, MCU, SBC, and MQTT broker, enabling users to remotely monitor the plants' conditions via a web browser on their smartphones or laptops. This IoT-based indoor hydroponic system showcases the potential of implementing IoT in agriculture and its contribution to fulfilling the food requirements of urban areas. However, the system relies heavily on technology, including the sensors, MCU, SBC, and network connectivity. If any of these components fail or experience issues, it could disrupt the functioning of the hydroponic system and affect crop production. Therefore, to deal with component failure, we will implement redundancy for critical components and network connectivity to avoid disruptions.

Our future research directions include the exploration of AI-driven features in our IoT system to enable predictive control of the hydroponic environment. Moreover, investigating the integration of renewable energy sources to power the system and developing data-driven algorithms for nutrient management, can further enhance the sustainability and efficiency of indoor hydroponic farming.

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