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IoT-enabled Greenhouse Systems: Optimizing Plant Growth and Efficiency

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ABSTRACT

Greenhouses have long been important in the advancement of agricultural operations because they provide regulated settings for optimal plant growth. With the introduction of real-time monitoring and automation capabilities, the Internet of Things (IoT) integration into greenhouse systems represents a revolutionary change. This abstract delves into the wider field of greenhouse technology, highlighting the role that IoT plays in improving agricultural in controlled environments. Conventional greenhouses provide plants with a protected environment, but they might not be as accurate or flexible. Intelligent control of environmental conditions is made possible by the introduction of IoT-enabled greenhouses, which utilize data exchange protocols, actuators, and sensors that are networked. The project aims to elevate traditional greenhouse models by integrating Node-RED and MQTT technologies. Transitioning from a Blynk-based prototype showcases the system's versatility. Other key components, including NodeMCU, sensors for real-time data, and LED lighting, collaborate to redefine controlled environment agriculture. The Raspberry Pi serves as a central hub, facilitating seamless communication through Node-RED and MQTT. This advanced greenhouse system harmonizes cutting-edge technologies, showcasing a commitment to sophistication and adaptability in agricultural practices.

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1. INTRODUCTION

The Internet of Things (IoT) refers to the network of physical objects or "things" embedded with sensors, software, and other technologies that enable them to connect and exchange data with other devices and systems over the internet [1]. These objects can range from everyday items such as household appliances and wearable devices to industrial machinery and infrastructure components [2]. IoT technology allows these objects to collect and transmit data about their environment, usage, and status, facilitating real-time monitoring, control, and automation of various processes. By enabling seamless communication between devices, IoT has the potential to revolutionize numerous industries, including agriculture, healthcare, transportation, manufacturing, and smart cities, among others. It promises to improve efficiency, optimize resource utilization, enhance decision-making, and create new opportunities for innovation and business growth. Thus, IoT is widely used in various fields for optimization and smart control [3-6].

As an example, IoT is used in energy harvesting purpose. It is used in energy harvesting by integrating sensors and devices with energy-harvesting technologies such as solar panels, microbial fuel cell [7-9], and plant microbial fuel cell [10-12]. These IoT devices can gather energy from their

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surrounding environment, such as sunlight, vibrations, or temperature differentials, to power themselves, eliminating the need for traditional batteries or wired power sources. This enables the deployment of IoT sensors in remote or hard-to-reach locations where traditional power sources are impractical or unavailable, thus expanding the scope of monitoring and control applications [13]. Thus, IoT combination with energy harvesting are used for powering sensors. In IoT applications, particularly in remote or distributed environments, powering sensors is a crucial consideration [14]. IoT devices often employ low-power microcontrollers and wireless communication protocols to minimize energy consumption [15-16]. Additionally, energy-efficient design principles, such as duty cycling and sleep modes, are implemented to prolong battery life. Moreover, advancements in energy harvesting technologies, as mentioned earlier, further contribute to powering IoT sensors without the need for frequent battery replacements or wired connections to grid for electricity [17-20].

Hence, similar concept of using IoT for power sensors for greenhouse for smart monitoring is implemented. In smart farming applications, IoT is utilized in greenhouse environments to monitor and control various factors such as temperature, humidity, soil moisture, and light intensity. IoT sensors deployed throughout the greenhouse continuously collect data on environmental conditions, which is then transmitted to a central management system. Farmers can remotely monitor and adjust these conditions in real-time, optimizing crop growth and resource utilization. Additionally, IoT platforms analyze the collected data to provide insights and recommendations for crop management, pest control, and irrigation scheduling, ultimately improving productivity and sustainability in greenhouse farming. The greenhouse industry is the world's fastest expanding industry. By separating the crop from its surroundings, the greenhouse offers some protection from the direct effects of the outside weather. This makes it possible to cultivate crops that would not otherwise be able to be produced at that site. The greenhouse enclosure enables the manipulation of the crop environment.[21] With this asset, the farmer can enhance cultivation in a way that best suits the needs of the plants. Increased crop yield, longer production time, improved quality, and reduced usage of protective pesticides are the results.

Research in [22] presents a study conducted to maximize the circumstances for plant growth, the study focuses on the design and implementation of a greenhouse monitoring and control system utilizing Node MCU ESP 8266. The writers stress the value of technology developments in agriculture, especially when it comes to using the internet to monitor greenhouses. The utilization of sensors such the LDR light sensor, soil moisture sensor, and DHT11 temperature and humidity sensor—all of which are coupled to the Node MCU ESP8266 microcontroller—is also covered in the paper. The project delves into creating an advanced greenhouse system, employing contemporary technologies like the Internet of Things (IoT) to enhance controlled environment agriculture. Greenhouses, as covered structures, furnish regulated climatic conditions, establishing optimal growth microenvironments for plants. From temperature control to carbon dioxide concentration, reduced pest exposure, and humidity management, greenhouses offer advantages over traditional outdoor farming.

Node-RED is a free server and web GUI built on JavaScript that the project uses to create a reliable and secure communication infrastructure. Node-RED solves security and privacy issues by enabling greater control and ownership of data, in contrast to third-party apps. This server offers an adaptable and user-friendly web interface for system management, enabling the integration of several hardware components, application programming interfaces, and web services.

This Internet of Things greenhouse project uses MQTT (Message Queuing Telemetry Transport) as its communication protocol, while Mosquitto acts as the MQTT broker. MQTT is well-known for its simple, publish/subscribe architecture, which makes it perfect for effective machine-to-machine communication. Targeted connection inside the IoT greenhouse system is ensured and flawless data interchange between devices is made possible by the NodeMCU's MQTT communication with the Raspberry Pi server. Raspbian is an operating system based on Linux that is tailored specifically for the Raspberry Pi. Raspbian contributes to the stability and dependability of the project by serving as the basis for hosting and maintaining the system components.[23] A progressive approach to greenhouse systems is represented by the integration of IoT technologies, such as NodeMCU, sensors, LED lights, Raspberry Pi, Mosquitto, and Raspbian. By delivering real-time monitoring, precise control, and user-friendly experiences, this cooperative synergy hopes to herald in a new era of intelligent and flexible controlled environment agriculture.

It is inherently difficult for traditional greenhouse systems to monitor and regulate critical environmental parameters including soil moisture, temperature, humidity, and light levels.[24] plant growth optimization is frequently hampered by the lack of a strong monitoring and control system, which results in subpar yields and resource use. the flexible and responsive real-time nature of conventional systems is insufficient to meet the changing and dynamic demands of contemporary agriculture. By utilizing NodeMCU v3's capabilities, the proposed solution seeks to address these issues and transform greenhouse management. the traditional method struggles to give farmers thorough insights on the greenhouse environment, which hinders their ability to make wise judgments. by integrating NodeMCU v3, the project attempts to construct a sophisticated monitoring and control system that gives real-time data on soil moisture, temperature, humidity, and light levels. In addition, the project aims to use node-red and MQTT to create a self-hosted iot infrastructure. concerns regarding data security, privacy, and personalization are raised by the fact that many modern greenhouse systems rely on third-party applications. the greenhouse system's ability to adjust to demands and specifications is restricted by the lack of a specialized and modifiable infrastructure.

In addition to filling in the gaps in current conventional greenhouse systems, the small iot greenhouse system envisioned in this project is meant to pave the way for future innovations. not only are immediate problem solutions prioritized, but also building a platform that may change with time. the suggested solution's essential elements of flexibility and upgradeability guarantee that the system will adapt to new developments in technology and agricultural methods. The difficulties and unresolved concerns in integrating iot technology in greenhouse farming are the focus of the journal "a survey on enabling technologies, applications, and protocols." these difficulties include issues with privacy and security, a lack of connectivity, the layout of the sensor distribution network, data processing capacity, the choice of technology, salinity of the soil, a lack of government backing, expensive marketing, a large investment, and a lack of interoperability. the document also emphasizes the need of addressing both technical and non-technical barriers to enable the widespread adoption of iot technology in greenhouse agriculture, as well as the need for in-depth analysis and comprehension of the state of research in iot-based greenhouse farming.[25]

A complete and cutting-edge greenhouse system that goes above and beyond accepted methods is the goal of the project. The project entails the creation of a connected greenhouse. Blynk is used for testing and prototyping at first, and later, a self-hosted solution with Node-RED and MQTT is used for more customization and management. The incorporation of IoT technology to facilitate automation, upgradability, and real-time monitoring is part of the scope. Enhancements in aesthetics, safety protocols, and thorough documentation are essential elements that guarantee a safe and easy-to-use greenhouse setting.

The smart global agriculture market is expected to reach $15.3 billion by the end of 2025.[26] Its development is greatly aided by new inventions and technologies such as big data, blockchain, machine learning, artificial intelligence (AI), data analytics, Internet of Things (IoT), and data analytics. [27-31] The Internet of Things (IoT) is one of the most promising enablers and is thought to represent a paradigm change in the development of smart agriculture [32], and it is anticipated to obfuscate the distinctions between the real and virtual worlds. This is accomplished by giving things (i.e., machines, gadgets, and objects) processing capacity and linking them so they may share information and communicate with one another without the assistance of a human.[33-34] The project's overarching goal is to showcase the possibilities of contemporary technologies in controlled environment agriculture by offering gardening lovers a flexible and advanced greenhouse system.

An innovative approach to resolving problems in modern agriculture, including labour-intensive procedures, limited water resources, and crop vulnerability to disease, is the suggested Internet of Things (IoT) smart greenhouse. The greenhouse's advanced array of sensors and automation technologies allow for accurate monitoring and control of critical factors that are necessary to plant growth. Solar energy is used in conjunction with a strong battery and inverter system to provide sustainability and independence. Real-time data visualization on an intuitive webpage providing insights into temperature, humidity, light intensity, soil moisture, and water levels is made possible by the system's connectivity with the Internet of Things (IoT). Additionally, the addition of manual control functions improves responsiveness and flexibility, giving farmers a complete instrument to manage the challenges of contemporary agriculture and lessen the effects of seasonal changes. [35]

The energy-efficient features and cost savings from large-scale manufacture of LED lighting have attracted a lot of academic interest in recent years. There is a significant research gap in the context of horticulture, even though numerous studies have examined control technologies that optimize energy savings and aspects like human comfort, colour temperature, and daylight harvesting in residential and commercial settings. LEDs are becoming more and more popular in horticulture due to their energy-saving qualities, controllability, and compatibility with Internet of Things technology.

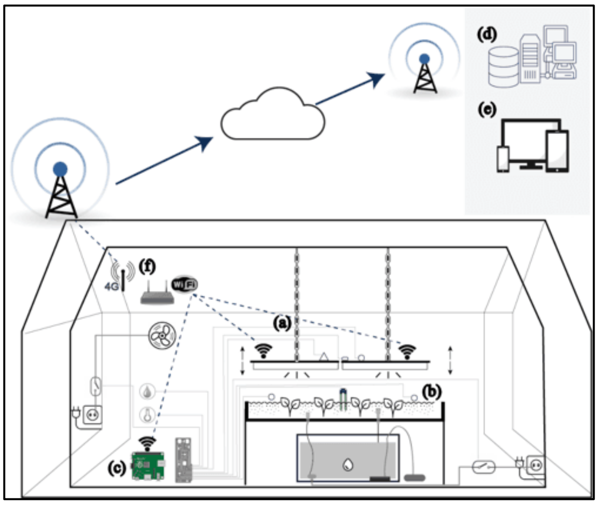


Fig. 1. Overview of the testbed greenhouse environment

It provides an adjustable lighting system with conditions for plant growth that can be customized, combined with Internet of Things technology for remote monitoring and control. With an emphasis on scalability, low maintainability, high flexibility, automation, and cheap cost, the testbed's design and development methodology offer a potential path forward for the advancement of research in intelligent LED lighting control for horticulture in greenhouse situations. [36]

Farmers benefit from Automated Greenhouse Systems, which employ the Internet of Things (IoT) to control environmental conditions, including crop health assessment through image analysis. Two main things typically impact greenhouses: plant diseases and weather patterns that cause productivity to decline. The research suggests a completely automated greenhouse with data protection and a less expensive image evaluation framework for the plant disease analysis. The Raspberry Pi, MSP432 microcontroller, temperature, moisture, and humidity sensors, as well as the OpenCV image inspection system, make up the prototype of the suggested system. When predefined threshold values are reached, MCU MSP432 uses relays to operate the actuators and motors. The Extended Tiny Encryption Algorithm (XTEA) is used to provide embedded data security in the suggested design. Finally, the cloud-based application allows the farmers to become acquainted with the suggested framework. The farmers can remotely assess and manage the ecology of their greenhouse thanks to the autonomous framework. [37]

The importance of greenhouses in maximizing plant development conditions and raising crop yield is highlighted in the introduction. This project explores the idea of the Internet of Things, highlighting how it may be used to connect actual objects and make data sharing easier. It goes over current techniques for controlling and monitoring greenhouse environments, such as SMS-based systems and ZigBee module-based wireless climate monitoring. A crucial contrast is shown between several communication systems, including Wi-Fi and SMS. They introduce the hardware components of the proposed system, which include motors, sensors, and Arduino UNO. The integration of fuzzy logic for decision-making and the Internet of Things application that uses ThingSpeak as a cloud server are described in depth. [38]

Eighty percent of Vietnam's GDP comes from agriculture, making it one of the emerging nations. Vietnam's agricultural output, along with that of other agricultural nations worldwide, has been severely impacted by global climate change. Due to their physical labor and lack of scientific foundation, farmers frequently squander resources during irrigation and fertilization, which raises unneeded expenses. Climate change is also causing a depletion and degradation of water resources, which has an impact on agricultural production quality. To support farmers with crop care, reduce costs, and boost labor productivity, the authors investigate and integrate technologies in agricultural production such as IoT, smart sensors, MQTT, intelligent pumping systems, and edge computing to design automatic or semi-automatic irrigation systems. [39]

The article "IoT-Based Smart Agriculture Aid System using Raspberry Pi" offers a solution to the problems farmers face when trying to manage soil quality and water distribution in agriculture. The authors emphasize the importance of agriculture as a crucial profession and the rising demand for fresh food production in their opening paragraph. They draw attention to the problems with agricultural water use and the demand for sustainable methods. The proposed solution involves the development of an IoT-based smart agricultural aid system using Raspberry Pi. The system utilizes various sensors, including a capacitive soil moisture sensor, DHT-11 humidity temperature sensor, rain sensor, and pH sensor, to monitor and control irrigation and soil conditions. The Raspberry Pi serves as the central control unit, facilitating data collection, analysis, and remote monitoring through ThingSpeak server.[40]

The creation of an Internet of Things-enabled, machine learning-module-equipped, sustainable automated greenhouse design is covered in the research article. Through the integration of IoT technologies for remote greenhouse monitoring and control, the suggested system seeks to increase the sustainability of agricultural. The two primary areas of emphasis for the proposed effort are energy management and soil and crop management. The system uses a variety of sensors and parts that are connected to a NodeMCU and Raspberry Pi board to monitor soil moisture, air quality, temperature, and sun exposure. Platforms like ThingSpeak and Blynk are utilized for storing and analysing the acquired data. The system also incorporates machine learning algorithms for irrigation control and soil prediction. Finally, an approach to tracking and controlling soil conditions in agriculture is provided by the Internet of Things-enabled intelligent soil management system. [41]

The goal of the study is to design a prototype smart greenhouse system that can use Internet of Things (IoT) technology to assess temperature, humidity, and soil moisture. The research addresses the drawbacks of standard greenhouse irrigation systems, including high human contact, expense, and water usage. To improve sustainability and energy efficiency, the system also includes a solar power system to deliver electricity to the electrical components. The use of IoT technology to smart farming is covered, including temperature-based ventilation system control in greenhouses, smart irrigation systems, and IoT adoption in agriculture. The utilization of solar energy as an alternative energy source and its potential to improve agricultural practices' energy efficiency are also included in the literature study. Additionally, it highlights how crucial automated agricultural systems—like ventilation fans and water pumps—are to maximizing resource efficiency and raising plant yields. [42]

The creation of a smart environment for plant growth is discussed in the paper through the implementation of an Internet of Things-based greenhouse monitoring and controlling system. The system focuses on adjusting characteristics like as soil moisture, light intensity, temperature, and humidity to satisfy the individual needs of crop production.

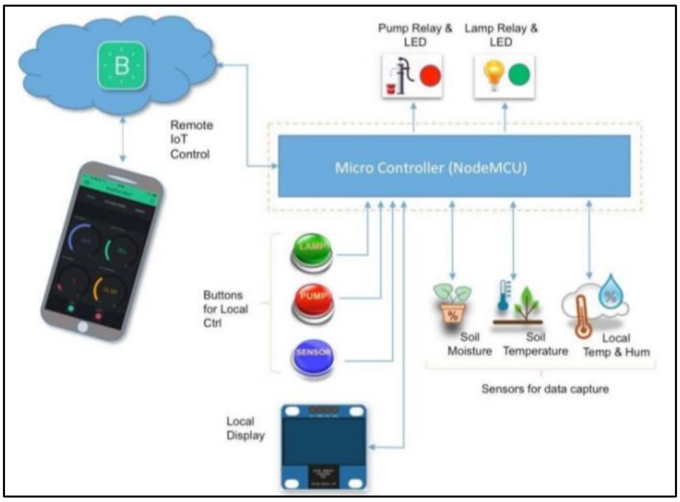


Fig. 2. System Overview [43].

The soil moisture sensor, LDR sensor, and DHT22 (temperature and humidity) sensor are some of the sensors it uses to gather data. This data is processed and used to manage many factors, including motors, water pumps, exhaust systems, and light systems. Farmers can get real-time environmental data on their smartphones by connecting the system to wireless internet or IoT platforms such as Telegram bot, thanks to the NodeMCU ESP8266 module. The use of technology in agriculture is emphasized to address the problems caused by disease outbreaks in traditional farming methods and changing weather patterns to achieve effective and sustainable agricultural production.[43].

The design of an automated, smart, solar-powered greenhouse system is discussed in the journal with the goal of increasing agricultural yield in Cameroon, specifically to produce off-season crops. The system incorporates several modules, such as an Arduino and Internet of Things (IoT)-powered solar power system and the physicochemical parameters required for vegetable development. It also includes an Android app that allows you to monitor and analyse the metrics from any Wi-Fi-enabled device. In addition to highlighting the need of agriculture for economic growth—especially in developing or impoverished nations—the paper also underlines the requirement of accuracy in agricultural practices to maximize productivity, lower production costs, and use less water. It also covers the automation of the greenhouse, the calibration of a pH tester for controlling fertilizer, and the features of the power supply, such as the quantity of solar panels, battery capacity, and charge controller. The advantages of the solar smart and fully automated greenhouse system are highlighted in the study's conclusion. They also highlight the system's potential for improved productivity conditions and ecological benefits. The paper also includes references to technical literature and relevant studies, providing in-depth understanding of the design and [44].

2. METHODOLOGY

2.1 Block Diagram

system's overall effectiveness. The Arduino IDE is essential for programming the NodeMCU microcontroller since it makes sure that it follows the pre-established guidelines and features. A smartphone or online dashboard serves as the interface for monitoring and operating the entire system, ensuring user-friendly engagement. Users can monitor greenhouse conditions and make educated decisions from anywhere with remote access to this user-friendly dashboard, which is hosted on the Raspberry Pi. To summarize, the block diagram illustrates a comprehensive and networked system intended to maximize greenhouse conditions by means of astute sensor data processing, efficient control systems, and easily navigable interfaces.

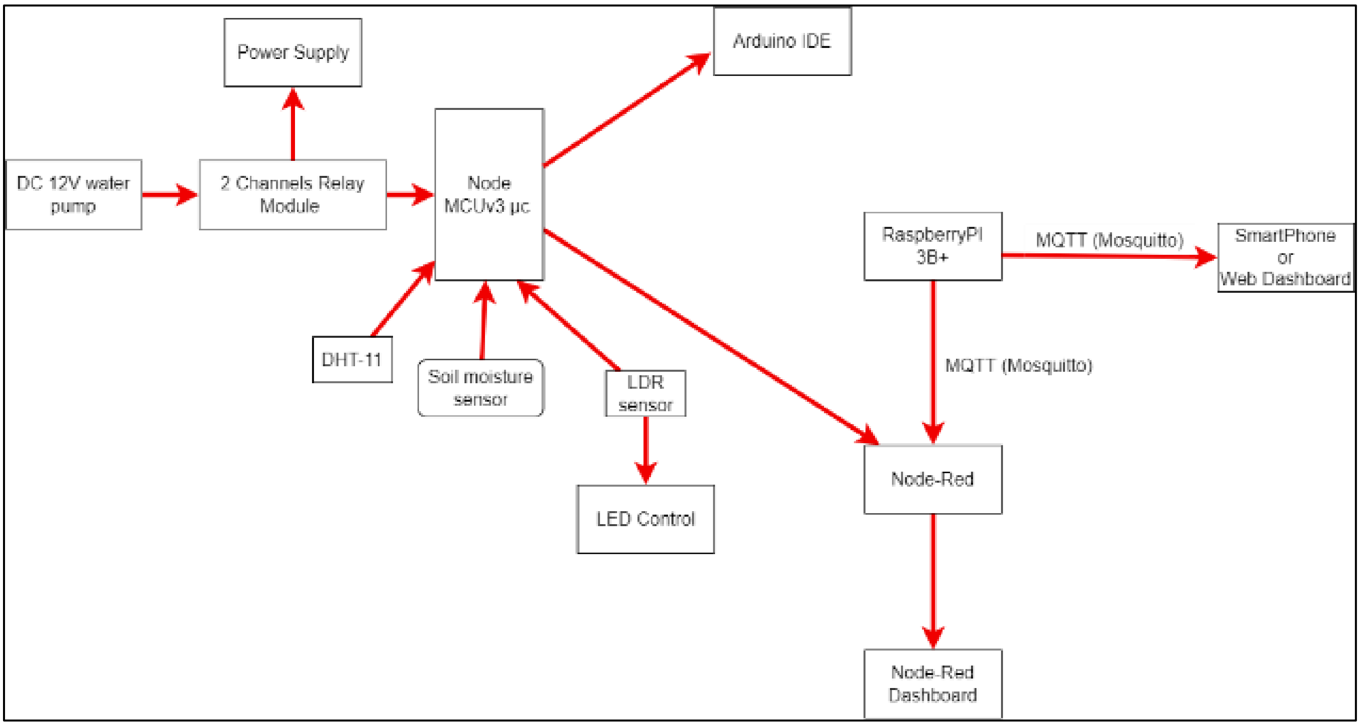


Fig. 3. Block Diagram of the Greenhouse System

The block diagram from Figure: 3.2 consists of various essential elements that work together to coordinate an advanced greenhouse management system. The power supply, which supplies the energy required to keep the system running, is at its core. The water pump is a crucial element that controls the flow of water to plants in the right amounts. The relay module, which acts as a switch and controls the water pump in response to signals it receives, facilitates this operation. The NodeMCU microcontroller is the brains of the system; it oversees monitoring sensor data and directing the movements of other parts. The DHT-11 sensor is one of the sensory devices that monitors temperature and humidity levels carefully, providing vital information to the system. [45] Concurrently, the soil moisture sensor determines how much water is in the soil, which helps with irrigation decisions. Simultaneously, the LDR sensor continuously measures ambient light levels, which is essential to comprehending how environmental factors affect plant development.[46] It is assumed that the LED control module controls LEDs, maybe offering visual cues or regulating lighting in the greenhouse. The Raspberry Pi boosts the system's capabilities by adding more software components and more computer power. One of the most important improvements is Node-RED, a visual programming tool that simplifies device control and data processing. The MQTT communication protocol makes it easier for software and devices to communicate data seamlessly, which improves the

2.2 Flowchart

The sequence of events that an automated irrigation system intended for gardens or plants goes through is shown in Figure 4, the flowchart that is provided. Commencing with the Arduino IDE downloading code to the NodeMCU microcontroller, the system executes data collecting through three sensors: the DHT-11 sensor for temperature and humidity, the LDR sensor for light intensity, and the soil moisture sensor. The NodeMCU performs data processing and decision-making by comparing soil moisture levels to a predetermined threshold and analysing additional control logic triggers after data capture. Important parts of the system are activated when the predetermined circumstances are met. This consists of an irrigation pump powered by a DC 12V solid state relay, an integrated LED strip that might function as an indicator for active watering, and a solid-state relay that regulates pump operation. Simultaneously, the NodeMCU publishes the gathered data to a MQTT broker, probably for additional analysis, and feeds real-time sensor readings to the serial monitor for preliminary testing and debugging. Control and data visualization are made possible via the Raspberry Pi and Node-RED. It gets data from the MQTT broker, processes it, and then updates the Node-RED dashboard with the most recent sensor data. The automated watering system's operational cycle is complete when the flowchart ends at the end state. By adjusting intelligently to changing climatic circumstances, this automated watering system maximizes plant care. Real-time data on the Node-RED dashboard helps to further visualize the system's operation.

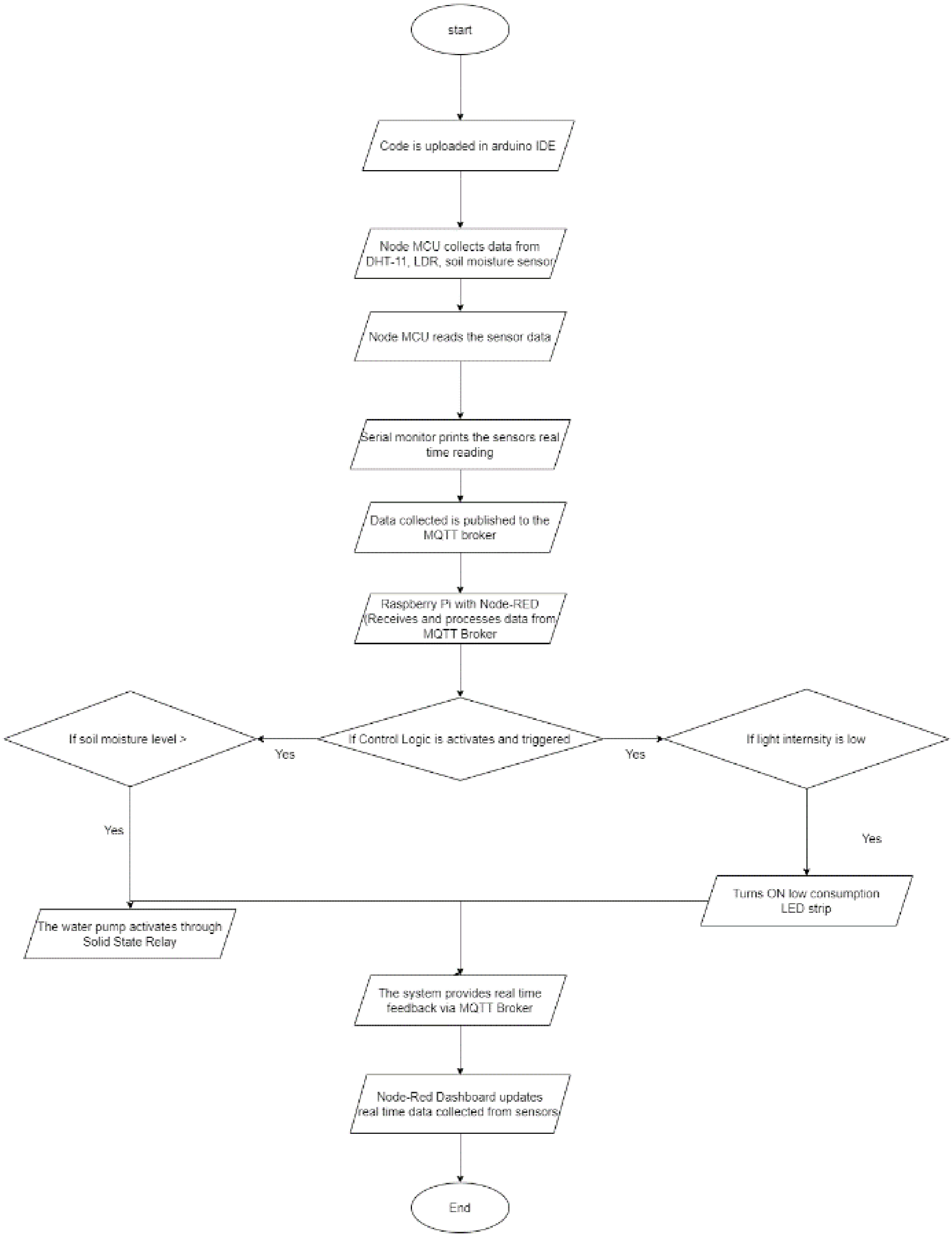


Fig. 4. Block Diagram

2.3 Schematic design

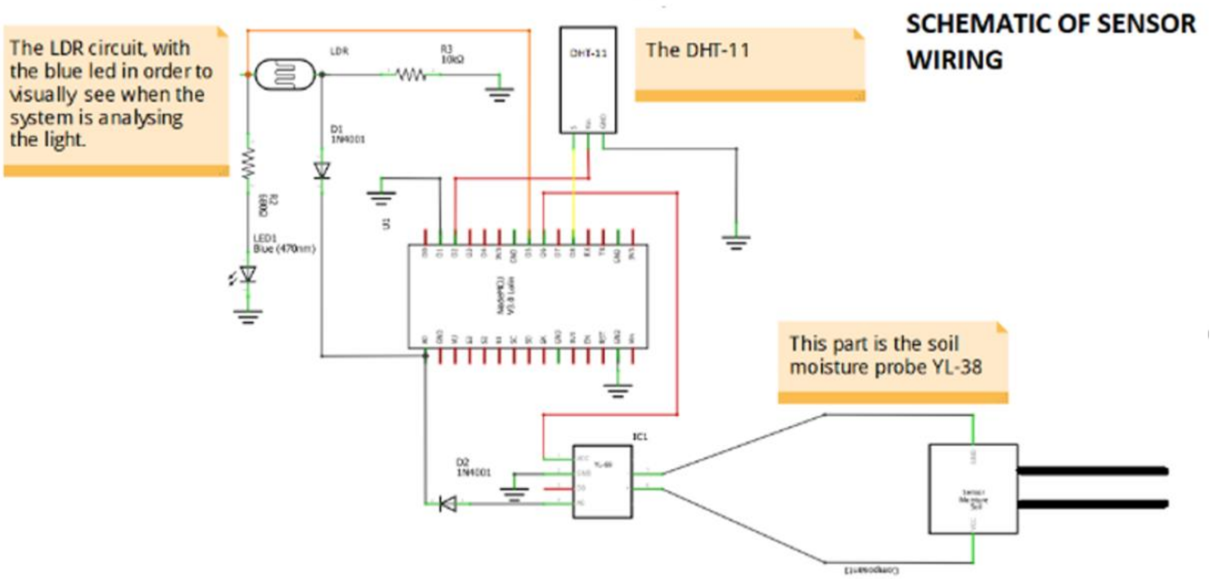


Fig. 5. Simulation

The schematic design shows the wire connections for the NodeMCU microcontroller, DHT-11 sensor, soil moisture sensor, and LDR (light dependent resistor), among other parts of the Internet of Things greenhouse system.

The key components of the wiring are explained by the following main points:

a. NodeMCU Initialization (D1 to GND):

The NodeMCU's D1 port is connected to GND in order to enable the NodeMCU to reload and initiate the code following a power cycle. Without this connection, the code can be forgotten if the power wire is disconnected and then rejoined.

b. Multiplexing for Analog Sensors (A0, LDR, and Soil Moisture):

Multiplexing is used since the NodeMCU has only one analog port (A0), while two sensors (LDR and soil moisture) produce analog results. One sensor at a time must be turned on selectively, its value must be read, and the procedure must be repeated for the other sensor. This enables the one analog port to be used effectively.

c. Diodes for Sensor Communication (1N4004 Diodes):

When sensors are connected to the analog port A0 for communication, diodes (1N4004) are utilized. Data interference between the sensors is avoided by the diodes. Without diodes, data could pass to the other sensor when one is turned on. In order to avoid cross-contamination, the diodes make sure that the current only goes from the sensor to the analog port.

d. Pull-down Resistor for LDR:

When connecting the LDR to the microcontroller, a pull-down resistor is used to provide steady readings. For the NodeMCU to provide accurate and trustworthy readings, this is necessary.

e. Connectivity of Sensors to NodeMCU:

DHT-11: VCC and NodeMCU D2 are connected, but NodeMCU D8 and GND are connected.

Soil Moisture: DATA is connected to NodeMCU A0 via a 1N4004 diode; VCC is connected to NodeMCU D6; GND is connected to NodeMCU GND.

LDR: NodeMCU A0 is connected to the right leg (sense irrelevant) via a 1N4004 diode.

GND is connected to NodeMCU by a 10 K resistor, while the left leg is connected to NodeMCU via D5.

The schematic diagram's comprehensive explanation guarantees correct wiring and configuration, facilitating the IoT greenhouse system's seamless component integration.

2.4 Connections

Figure 6 shows the top view and rear consist of the circuit of the greenhouse system that consists of the components integrated for this project:

- The power supply provides energy to fuel the entire system.
- The water pump is responsible for distributing water when needed.
- The relay module acts as a switch, controlling the water pump based on signals it receives.
- The NodeMCU microcontroller serves as the system's brain, managing sensor readings and directing other components.
- The DHT-11 sensor measures temperature and humidity levels.

- The soil moisture sensor monitors the water content within the soil.
- The LDR sensor tracks ambient light levels in the environment.

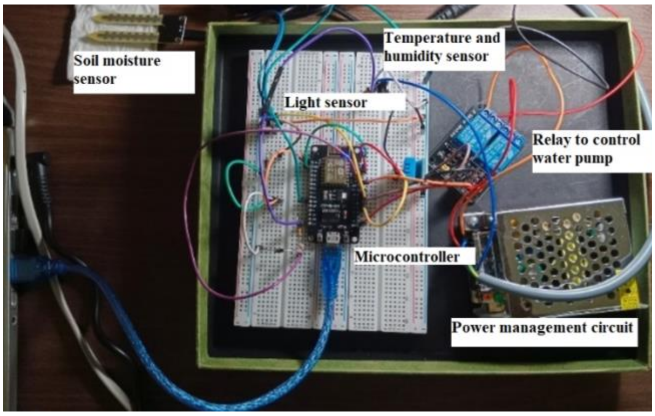


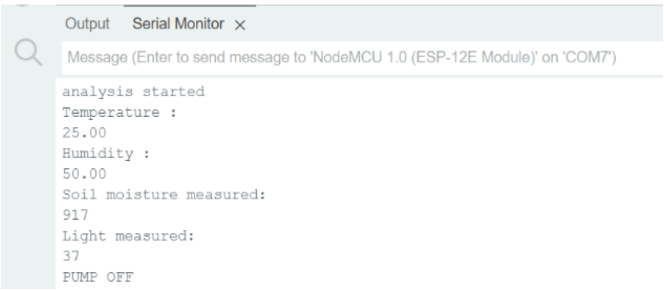
Fig. 6. Top View

3. RESULTS

The data gathered from several trials, each of which represented a unique measurement for different environmental parameters in a specific context—likely a greenhouse or other similar setting—is presented in an organized manner in this table. The soil moisture, humidity, temperature, and light levels are recorded for each of the five trials that are included in the table 1.

Table 1. Trial results for sensor functionality

Measurement	1st Trial	2nd Trial	3rd Trial	4thTrial	5thTrial
Soil moisture	919	917	800	835	745
Humidity	50	50	43	42	48
Temperature	25^{0}C	25^{0}C	23^{0}C	24^{0}C	25^{0}C
Light levels	37	42	30	25	9



```
analysis started
Temperature :
25.00
Humidity :
50.00
Soil moisture measured:
917
Light measured:
37
PUMP OFF
```

Fig. 8. Result of the readings in serial monitor

4. LIMITATIONS & RECOMMENDATIONS

4.1 *Limitations*

Although the project is a success and meets all the objectives set, however, it is still faces some of the limitations as elaborated below:

- Reliance upon Internet Access:

The system's ability to monitor and control remotely is mostly dependent on internet connectivity. The user may have difficulties when trying to access the dashboard or remotely operate the greenhouse in the event of network problems or outages.

- NodeMCU (esp 8266) connectivity issues:

NodeMCU faced issues with the connection of PORT in the laptop. There was a need to keep installing the driver due to a esp 8266 port compatibility issue. [47]

- Power Reliance:

The NodeMCU and Raspberry Pi are assumed to have a constant power source in this project. Power outages may have an impact on how well the greenhouse automation system works.

4.2 *Future Works Recommendations*

- *Sensors integration:*

As each research faces limitations, they also open up for the possibilities of improvement and enhancement. Hence is the future works recommended for this project can be to include the sensors below to enhance the environment monitoring capability:

a. Nutrient sensors:

These sensors can provide information on the nutritional makeup of the soil by detecting particular nutrients like potassium, phosphorus, and nitrogen.

b. DHT-22 sensors:

The DHT22, at 98.15%, the DHT11, at 97.19%, and the DS18B20 sensor, at 99.05%, showed the best accuracy performance in the field testing. According to these findings, the DS18B20 sensor outperforms the DHT22 and DHT11 sensors in terms of accuracy. [48] Considering the budget opting for a DHT22 is little more pricey but far accurate than the DHT11 sensor.

c. Soil pH Sensors:

Knowing the acidity or alkalinity of the soil requires regular monitoring of its pH levels. Certain crops grow best in a range of pH values, and keeping the pH of the soil at its ideal level is essential for the availability of nutrients. Soil pH sensors can provide important information for accurate pH level regulation.[48]

d. Gas Sensors:

Including gas sensors can help keep an eye on the greenhouse's air quality. This contains sensors for gases like ethylene and carbon dioxide (CO2). While ethylene levels might affect the ripening of some fruits, maintaining ideal CO2 levels is essential for photosynthesis.

e. Light Spectrum Sensors:

While more sophisticated sensors can offer information on the light spectrum, basic light sensors are frequently employed to assess total light intensity.[49] This involves determining the concentrations of particular wavelengths, which is advantageous for maximizing artificial lighting settings for plants.

- *Prototype Enhancement Recommendations*

Summarised below are some future works recommendation in upgrading the functionality of an IoT-enabled Greenhouse Systems:

f. Environmental Monitoring:

Consider adding sophisticated environmental monitoring technologies such as spectral sensors for exact light spectrum assessment. By adjusting the lighting to each plant's unique requirements, these sensors can maximize photosynthesis and overall development. Investigating hyperspectral or multispectral imaging methods may also provide information about the health and stress levels of plants.[50]

g. Energy-Efficient Lighting Strategies:

Examine energy-efficient lighting techniques, such as the incorporation of intelligent LED systems including modifiable spectrum.[51] This enables dynamic control over color temperature and light intensity, optimizing energy usage while satisfying the unique light needs of diverse crops at different stages of growth.

h. Incorporating Artificial Intelligence and Machine Learning:

In the ongoing quest for sustainable agriculture, future advancements in IoT-enabled greenhouse systems could focus on integrating artificial intelligence (AI) and machine learning (ML) technologies to optimize plant growth, resource management, and environmental sustainability [52]. AI algorithms can analyse vast amounts of sensor data collected by IoT devices to predict plant behaviour, identify patterns, and recommend tailored cultivation strategies. ML models can adaptively control environmental factors such as temperature, humidity, and light intensity to create optimal growth conditions while minimizing resource consumption. Additionally, AI-powered pest and disease detection systems can swiftly identify and mitigate threats, reducing the need for chemical interventions and promoting healthier crops. By harnessing the synergy between IoT, AI, and ML, future greenhouse systems can revolutionize agriculture, maximizing yields while minimizing environmental impact.

i. Integrating with Advanced IoT Sensors:

In advancing IoT-enabled greenhouse systems, integrating with Advanced IoT Sensors presents a promising avenue for enhancing precision agriculture [53-54]. Future efforts could prioritize the development and integration of sensors capable of measuring a broader range of environmental parameters with higher accuracy and granularity. These sensors could include advanced soil sensors for precise monitoring of moisture content, nutrient levels, and soil health indicators. Additionally, integrating spectral sensors could enable real-time monitoring of plant health, detecting early signs of stress or nutrient deficiencies. Advanced IoT sensors for monitoring air quality, including pollutants and CO2 levels, could further optimize growing conditions. Moreover, incorporating wireless sensor networks and edge computing capabilities could enhance data collection efficiency and enable real-time analysis for proactive decision-making. By leveraging the capabilities of Advanced IoT Sensors, future greenhouse systems can achieve unprecedented levels of precision, productivity, and sustainability in agricultural practices.

j. Enabling Rechargeable Power Station:

Innovations in IoT-enabled Greenhouse Systems can be achieved by integrating rechargeable power stations, ushering in new levels of energy efficiency and sustainability [55]. Future endeavours could focus on developing power stations equipped with renewable energy sources such as solar panels or wind turbines, enabling off-grid operation, and reducing dependency on traditional power grids. These rechargeable stations could store excess energy during periods of high production and distribute it during peak demand, ensuring a stable and reliable power supply for IoT devices within the greenhouse. Additionally, integration with smart energy management systems could optimize energy usage based on real-time data, prioritizing critical functions and minimizing wastage. Moreover, incorporating energy storage technologies like advanced batteries or capacitors could enhance system resilience and provide backup power during outages. By harnessing rechargeable power stations, future greenhouse systems can achieve greater energy autonomy, resilience, and sustainability, driving forward the evolution of smart agriculture.

5. CONCLUSION

In conclusion, the implementation of an IoT greenhouse monitor system using NodeMCU and MQTT integration offers a promising solution for enhancing agricultural practices with efficiency and sustainability. Through real-time monitoring and control capabilities, this system empowers growers to optimize resource utilization, mitigate risks, and maximize crop yield. The utilization of MQTT protocol ensures seamless communication between devices, enabling remote access and management of greenhouse conditions. As technology continues to evolve, further advancements in IoT-enabled agriculture hold the potential to revolutionize the way we cultivate crops, ultimately contributing to a more sustainable and resilient food production system.

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