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IoT-Enabled Smart Greenhouse: Real-Time Monitoring and Automated Control for Efficient Agriculture

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Abstract: The growing need for efficient resource management in agriculture, particularly in water and energy conservation, has led to the emergence of smart technologies. This research focuses on designing and implementing an IoT-enabled smart greenhouse system aimed at optimizing environmental conditions for plant growth through real-time monitoring and automated control. The system integrates various sensors, including temperature, humidity, and SM sensors, with a central ESP32 microcontroller to collect and analyze data. Actuators such as fans, water pumps, and lights automatically adjust the greenhouse conditions based on sensor feedback. This reduces the need for manual intervention, making the system more efficient and less labour-intensive. The proposed system has wireless sensor networks (WSN) and cloud computing capabilities, allowing farmers to remotely monitor and control the greenhouse environment using a mobile app interface. The real-time data collected by the sensors is stored and processed in the cloud, enabling detailed data analysis and the identification of environmental trends. The smart irrigation system ensures optimal water usage, contributing to the conservation of this critical resource. Experimental results indicate significant improvements in resource management, with notable reductions in water consumption and energy usage. The system is scalable and can be customized for different crops and climatic conditions, offering a versatile solution for modern agriculture. By leveraging IoT technologies, this smart greenhouse system enhances crop yield while reducing resource waste, making it a sustainable option for small- and large-scale agricultural operations.

Keywords: IoT, smart greenhouse, real-time monitoring, automated control, wireless sensor networks, ESP32 microcontroller, sustainable agriculture, smart irrigation, resource efficiency.

1. INTRODUCTION: Many people receive employment, food, and raw materials from agriculture, which are essential to maintaining human life [1]. With the ever-increasing food demand due to population rise, agriculture must adapt to technological advancements that enhance productivity while conserving critical resources such as water and energy [2]. Traditional agricultural practices often involve inefficient, labour-intensive processes that lead to the wastage of resources. In particular, irrigation systems and climate control in greenhouses frequently require manual monitoring and adjustment [3], making it difficult to ensure that crops receive the precise care they need for optimal growth [4][5]. This is where the incorporation of IoT technology offers a significant breakthrough.

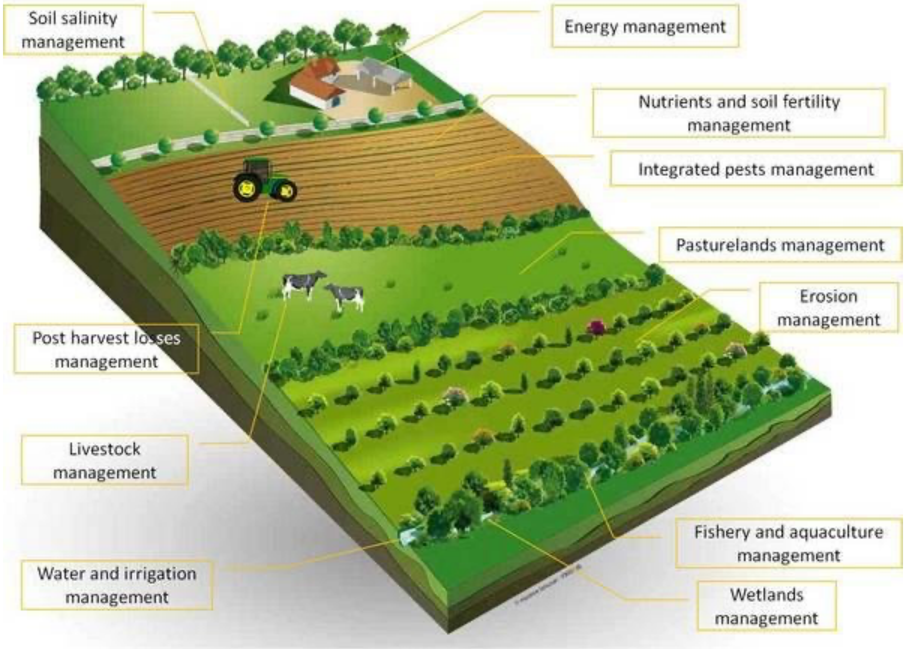

Figure 1: Sustainable agriculture platform [6]

The concept of a "smart greenhouse" leverages IoT technologies to transform conventional greenhouse operations into an automated and efficient system [7]. A smart greenhouse can track and monitor many environmental characteristics, including humidity, SM, temperature, and light intensity, using a network of sensors, microcontrollers, and actuators. These parameters are essential for creating the ideal conditions for plant growth, ensuring that crops thrive while minimizing the overuse of resources. In particular, the precise control of irrigation systems relies on real-time soil moisture data to help prevent overwatering or underwatering, which are common issues in traditional farming methods.

IoT technology has revolutionized various sectors, including healthcare, transportation, and industrial automation. Its application in agriculture, often referred to as "smart farming," has the potential to significantly improve food production, reduce environmental impact, and ensure the efficient use of resources [8]. The core of this innovation lies in using WSNs that allow for the continuous collection of data from the environment [9]. These data are transmitted to a cloud computing platform, where they can be analyzed to provide actionable insights. This data-driven method allows farmers to make informed decisions and optimize their agricultural techniques, improving crop yields and resource conservation.

This paper presents an IoT-enabled smart greenhouse system that automates the process of monitoring and controlling environmental conditions. The system is built on the ESP32 microcontroller, a powerful yet energy-efficient device capable of handling multiple sensors and actuators. The primary sensors used in this system include SM sensors, humidity and temperature, which provide real-time data on the GH environment. Based on the sensor feedback, the system can automatically control various actuators, such as water pumps, fans, and lights, to maintain the optimal conditions for plant growth.

One of the significant advantages of this smart greenhouse system is its ability to be monitored and controlled remotely via a mobile app. Farmers can access real-time data on their smartphones or tablets, allowing them to adjust the system without being physically in the greenhouse.

IoT in Agriculture: A Growing Necessity: Agriculture transforms digitally as farmers and agricultural stakeholders recognize the need for more efficient and sustainable farming practices [10]. IoT-based systems are at the forefront of this transformation, offering new ways to monitor crops, soil, and environmental conditions [11]. With the ability to collect vast amounts of data through sensors, IoT devices allow farmers to gain deeper insights into their fields and crops, improving productivity and reducing waste.

Greenhouses, in particular, can benefit from IoT technologies. In traditional greenhouse systems, maintaining the right environmental conditions often requires constant manual monitoring, which can be time-consuming and prone to human error. Moreover, temperature, humidity, and SM variations can lead to suboptimal conditions for plant growth, resulting in poor crop yields. Implementing IoT-enabled sensors and automated control systems can mitigate these issues by continuously monitoring the greenhouse environment and making real-time adjustments.

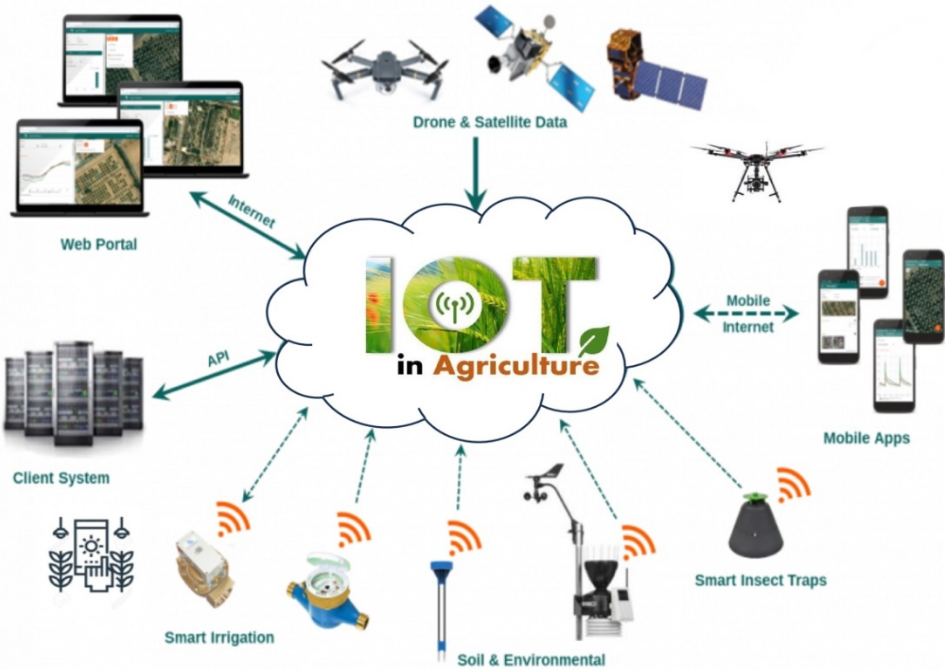

Figure 2: Smart agriculture with IoT apps [12]

System Overview: The IoT-based smart greenhouse system discussed in this paper is designed to monitor and control the key environmental parameters that affect plant growth. The system architecture consists of three main components: sensors, the ESP32 microcontroller, and actuators.

Sensors: Temperature and humidity sensors (DHT11) are used to measure the greenhouse's humidity and ambient temperature levels. These sensors provide critical data for maintaining the ideal climate conditions required by different crops. SM sensors assess the water content in the soil, guaranteeing that plants obtain the proper amount of water for optimal growth. These sensors help conserve water and promote sustainable farming practices by preventing over-irrigation or under-irrigation. Light sensors (LDR) are used to monitor the light intensity in the greenhouse. Light is essential for photosynthesis, and controlling light exposure is vital for maximizing plant growth.

ESP32 Microcontroller: The ESP32 microcontroller serves as the system's brain, receiving sensor data and controlling the actuators based on pre-programmed thresholds [13]. The microcontroller automatically triggers the necessary adjustments when the sensor data indicates that environmental conditions have deviated from the optimal range. For instance, if the SM level falls below a certain threshold, the microcontroller activates the water pump to irrigate the crops.

Actuators: The system employs several actuators, including fans, water pumps, and lighting. These actuators are responsible for adjusting the environmental conditions within the greenhouse [14]. The water pump, for example, ensures that plants are irrigated when the soil moisture levels drop, while the fans help regulate the temperature inside the greenhouse.

Remote Monitoring and Control: A key feature of the smart greenhouse system is its ability to be remotely monitored and controlled through a mobile app. The system uses cloud computing to store and process data, allowing farmers to access real-time information anywhere in the world. The mobile app provides a user-friendly interface for viewing sensor data, setting thresholds, and controlling the actuators. This level of automation reduces the need for constant human intervention and ensures that the greenhouse operates efficiently even when the farmer is not on-site.

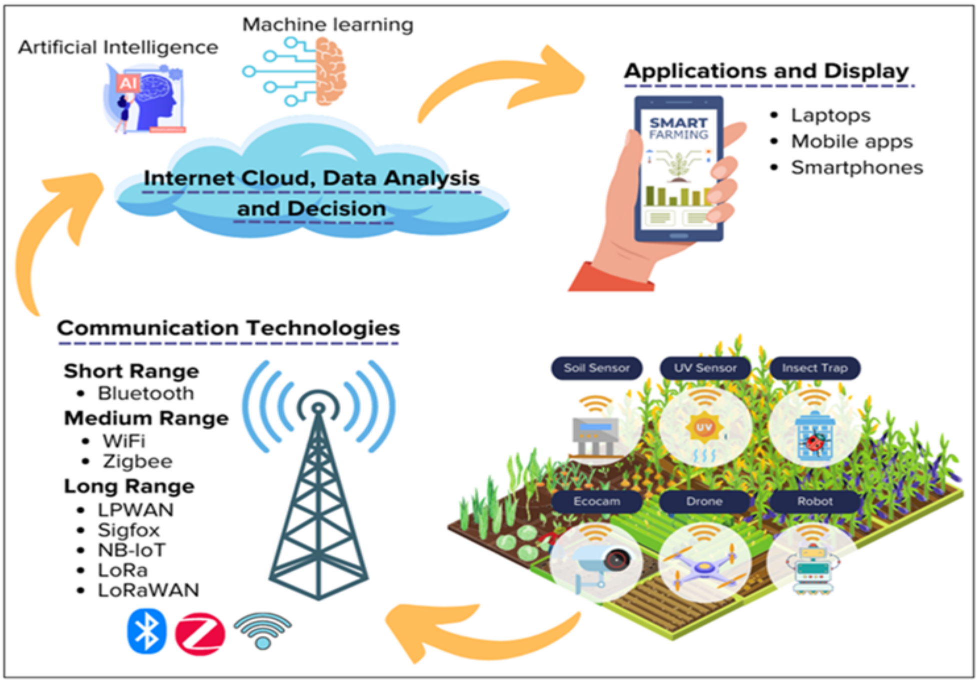

Figure 3: Comprehensive Architecture of Smart Farming: Monitoring Through End-Use Solutions [15]

Integrating IoT technologies into greenhouse farming is a major advance toward more efficient and sustainable agricultural practices. By automating the monitoring and control of environmental conditions, this smart greenhouse system reduces resource waste and enhances crop yields, offering a scalable solution for modern farming operations.

2. METHODOLOGY: The first goal of this paper is to develop an IoT-enabled smart greenhouse system that automates the monitoring and control of critical environmental conditions. The system's methodology revolves around integrating sensors, microcontrollers, actuators, and cloud computing to achieve real-time monitoring and automated adjustments. This section outlines the step-by-step methodology employed in designing, implementing, and testing the smart greenhouse system.

System Design: The system is designed with three major components: sensors for data collection, an ESP32 microcontroller for processing, and actuators for controlling environmental factors. The overarching architecture of the system ensures seamless communication between the sensors and the control system, allowing for real-time adjustments of the environmental conditions.

System Components:

ESP32 Microcontroller: The central processing unit that manages the input from sensors and controls the actuators based on predefined thresholds.

Sensors: Temperature and Humidity Sensor (DHT11): To measure the humidity and ambient temperature, Soil Moisture Sensor: To determine the soil's water content and make sure irrigation is done correctly, Light Sensor (LDR): To monitor light intensity and adjust lighting conditions when necessary.

Actuators: Water Pump: To automatically irrigate the crops based on soil moisture sensor data, Fans: To regulate the temperature within the greenhouse, Light System: To provide adequate lighting if needed.

Hardware Setup: The hardware setup involves the assembly of the sensors, ESP32 microcontroller, and actuators. The sensors are placed in different parts of the greenhouse to collect relevant data. The ESP32 microcontroller receives input from the sensors and triggers the appropriate actuators when the environment deviates from the desired conditions.

Sensing and Data Collection: The ESP32 microcontroller is connected to the sensors, which continuously collect environmental data such as light intensity, soil moisture, humidity, and temperature. The data is processed in actual time, encouraging prompt modifications.

Actuators and Control: The actuators (water pump, fans, and lighting) are connected to the microcontroller and are activated based on the sensor readings. For instance, if the soil moisture drops below a predefined threshold, the water pump is activated to irrigate the crops.

Software Development: The system is programmed using the Arduino IDE, which allows for easy integration with the ESP32 microcontroller. The following software components are developed:

Data Processing and Analysis: The ESP32 microcontroller is programmed to analyze the data received from the sensors in real time. Threshold values for each environmental parameter are predefined in the system. When these values are breached, the microcontroller activates the relevant actuators.

Wireless Communication: The ESP32 microcontroller is equipped with Wi-Fi capability, allowing it to send real-time data to a cloud platform. The ThinkSpeak IoT application is used to display and analyze the data on a dashboard, which can be accessed remotely.

Mobile App Interface: A user-friendly mobile application is developed to enable farmers to control and monitor the greenhouse remotely. The app receives actual data from the cloud, allowing users to view environmental parameters and adjust settings as needed.

IoT and Cloud Integration: The system leverages cloud computing to store and analyze sensor data. The ThingSpeak IoT platform is used to collect data from the ESP32 microcontroller, enabling remote monitoring and control. This cloud-based solution also provides long-term data storage, allowing farmers to examine past data and spot patterns that can optimize the growing conditions.

Data Transmission: Real-time sensor data transmission to the cloud using the Wi-Fi capabilities of the ESP32 microcontroller. The ThingSpeak platform provides a dashboard where users can visualize the data and monitor the status of the greenhouse.

Remote Control: The mobile application allows for remote control of the greenhouse by sending commands to the ESP32 microcontroller via the cloud. Users can adjust the thresholds for temperature, humidity, and soil moisture directly from their smartphones.

Testing and Evaluation: After setting up the system, it is tested in a controlled greenhouse environment. The sensors are used to measure the key environmental parameters, while the actuators are triggered based on real-time sensor data.

Performance Testing: The system is tested under various environmental conditions to ensure its reliability and efficiency. For instance, the soil moisture sensor is tested by artificially reducing the soil moisture level and observing whether the water pump is activated appropriately.

Data Accuracy: The accuracy of the sensor data is compared against standard measurements to ensure the reliability of the system. This involves calibrating the sensors to provide precise measurements.

System Scalability and Customization: The system is designed to be scalable, allowing for the integration of additional sensors or actuators depending on the specific requirements of different crops or climatic conditions. The system can be customized to handle larger greenhouses or different plant varieties by adjusting the threshold values in the microcontroller code.

3. WORKING OF THE IOT-BASED SMART GREENHOUSE SYSTEM: The smart greenhouse system works by continuously monitoring the environmental parameters within the greenhouse and automatically adjusting them to ensure optimal conditions for plant growth. The system integrates IoT technology, allowing for actual monitoring and control through a mobile app. The working process is outlined in the following steps:

Data Collection: The sensors are placed in the greenhouse and are connected to the ESP32 microcontroller. The sensors continuously collect actual data on the environmental conditions. For example, the DHT11 sensor measures temperature and humidity, while the soil moisture sensor monitors the water content in the soil.

Data Processing: The ESP32 microcontroller receives the sensor data and processes it according to predefined threshold values. If any environmental parameter exceeds or falls below the threshold, the system automatically triggers the appropriate actuator. For instance, if the temperature inside the greenhouse rises above the set limit, the microcontroller activates the fan to lower the temperature. Similarly, if the level of soil moisture drops below the threshold, the water pump is activated to irrigate the crops.

Automated Control: The system uses sensor readings to automatically modify ambient parameters. The water pump, fan, and lighting system are controlled by the microcontroller, ensuring that the greenhouse remains within optimal conditions for plant growth. This automation reduces the need for manual intervention, allowing the greenhouse to operate efficiently even without constant human supervision.

Remote Monitoring and Control: The ESP32 microcontroller is connected to the internet via Wi-Fi, enabling real-time data transmission to the ThingSpeak IoT platform. The mobile application interface allows users to remotely monitor the greenhouse's conditions. Users can access real-time data on their smartphones, view the status of the actuators, and make adjustments to the system. For example, if a user notices that the soil moisture level is too low, they can activate the water pump directly from the mobile app.

Cloud-Based Data Storage and Analysis: All sensor data is sent to the cloud for analysis and storage. The cloud platform provides long-term data storage, allowing users to track environmental trends and optimize their farming practices. The data can be visualized on a dashboard, assisting farmers in making defensible decisions about irrigation schedules, temperature control, and other aspects of greenhouse management. This system demonstrates a reliable and scalable solution for modern agriculture, reducing resource waste, improving crop yields, and enhancing the overall efficiency of GH operations.

4. RESULT AND DISCUSSION: The development and implementation of an IoT-based smart GH system successfully demonstrated the potential of technology in automating and optimizing agricultural processes. The system was able to monitor and control critical environmental parameters such as light intensity, soil moisture, humidity, and temperature in real time, thus creating an ideal environment for plant growth. The below graph represents sensor data over a 24-hour period. Below is an analysis of the results and key findings of the project:

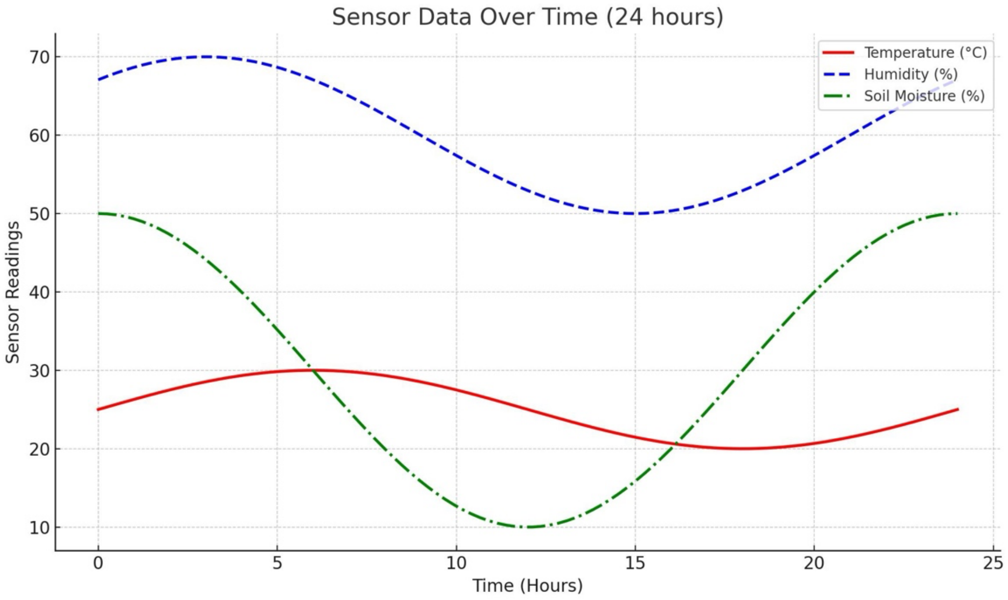

Figure: **Graph of Sensor Data**:

System Performance and Reliability: The smart greenhouse system performed effectively during the testing phase. The sensors continuously collected accurate real-time data, and the ESP32 microcontroller processed and responded to this data efficiently. The response time of the system, from data collection to actuator activation, was minimal. This fast and precise response ensured that the greenhouse environment remained within the optimal range for plant growth. For instance, when soil moisture levels fell below the set threshold, the system promptly activated the water pump to irrigate the crops. The temperature and humidity sensor (DHT11) accurately tracked changes in environmental conditions and triggered the fan and lighting system as necessary. The soil moisture sensor provided consistent feedback on the soil's moisture content, allowing for the efficient use of water resources.

Discussion: The system's ability to perform autonomously without human intervention proved its effectiveness. It eliminated the need for constant manual monitoring, reducing labour costs and human error. The performance also showcased the efficiency of using IoT and microcontroller-based solutions for agricultural applications.

Energy and Water Efficiency: One of the critical objectives of the smart greenhouse system was to optimize resource usage, particularly water and electricity. The system achieved this by only activating the water pump and lighting systems when necessary, based on real-time sensor data. The use of soil moisture sensors allowed for precise irrigation, ensuring that water was only supplied when needed, preventing both over-watering and under-watering. Similarly, the lighting and temperature control systems were only activated when environmental conditions exceeded the desired thresholds. This automation led to significant savings in energy, as the lighting and fan were not operating continuously but rather on demand.

Discussion: The results demonstrated the potential of IoT-enabled systems in conserving critical resources like water and energy. This aligns with global efforts to promote sustainable agriculture, particularly in regions where water is scarce. The system's ability to manage resources and monitor efficiently can be particularly beneficial for small-scale farmers looking to improve crop yields while minimizing resource wastage.

Remote Monitoring and Control: The integration of cloud computing with IoT allowed the greenhouse system to be monitored and controlled remotely via a mobile application. Users were able to access real-time data on their mobile devices, giving them the flexibility to monitor the greenhouse's conditions from any location. This feature significantly increased the convenience of managing the greenhouse, especially for users who could not be physically present at the site. The mobile app interface provided users with a comprehensive view of the greenhouse's parameters, allowing them to adjust thresholds and activate actuators when necessary. For example, a farmer could increase the irrigation frequency during hotter days without being on-site, ensuring the crops remained adequately watered.

Discussion: The remote monitoring capability added significant value to the system. Farmers could now have complete control over their greenhouse operations without being physically present. This feature can prove particularly useful in larger farms or in cases where farmers manage multiple greenhouses across different locations. The integration of mobile apps and IoT technology opens new possibilities for agricultural automation, making farming more accessible and efficient.

Scalability and Customization: The system was designed with scalability in mind, meaning it could be easily expanded by adding more sensors or actuators depending on the size of the greenhouse or specific plant requirements. The ESP32 microcontroller was capable of handling additional inputs, making the system adaptable for various agricultural applications.

Discussion: The system's scalability makes it suitable for different farming scenarios, from small greenhouses to larger commercial agricultural operations. By adjusting the threshold values in the microcontroller's programming, the system can be customized for different crops, seasons, or environmental conditions, providing a versatile tool for farmers.

Challenges and Limitations: During testing, a few challenges were encountered. For instance, the Wi-Fi signal strength had a significant impact on the system's ability to transmit data to the cloud. In areas with poor connectivity, the system's remote monitoring feature became less effective. This highlights the need for reliable internet infrastructure in rural areas for such IoT systems to function optimally. Additionally, while the system was able to automate most of the greenhouse processes, some manual interventions were still required, such as recalibrating sensors periodically or adjusting thresholds based on seasonal changes.

Discussion: The reliance on stable internet connections presents a limitation for deploying this system in regions with limited connectivity. A potential solution could be the integration of GSM modules or other communication technologies that do not rely solely on Wi-Fi. Moreover, adding machine learning algorithms to the system could allow it to learn from past data and automatically adjust thresholds for seasonal changes, further reducing the need for manual interventions.

5. CONCLUSION: This investigation successfully demonstrated the feasibility and effectiveness of an IoT-based smart GH system for automating the monitoring and control of critical environmental parameters. The system's design, which integrated sensors, microcontrollers, and cloud computing, allowed for actual data collection, analysis, and automated control of key environmental factors such as SM, humidity, and temperature.
The primary contributions of this research include:

Resource Efficiency: The system optimized the use of water and electricity, significantly reducing resource wastage through automated control based on real-time sensor data.

Remote Monitoring: The ability to control and monitor the greenhouse remotely through a mobile application increased convenience for users, making it easier to manage greenhouse conditions from any location.

Scalability: The system was designed to be scalable and customizable, making it adaptable to various agricultural applications, from small-scale greenhouses to larger commercial farms.

However, challenges such as reliance on internet connectivity and occasional manual interventions indicate areas for further improvement. Future work could focus on enhancing the system's self-learning capabilities using machine learning algorithms, improving communication infrastructure in rural areas, and expanding the system's scalability for larger agricultural operations.

Overall, the smart greenhouse system presents a promising solution for modern agriculture, addressing the growing need for efficient, automated, and sustainable farming practices. The integration of IoT and cloud technology into agricultural systems can play a crucial role in meeting the challenges of food security, water conservation, and climate resilience in the coming decades.

Abbreviations

IoT = Internet of Things
WSNs = wireless sensor networks
GH= Green House
SM= Soil Moisture

References

[1] Sridhar A, Balakrishnan A, Jacob MM, Sillanpää M, Dayanandan N. Global impact of COVID-19 on agriculture: role of sustainable agriculture and digital farming. Environmental Science and Pollution Research. 2023 Mar;30(15):42509-25.

[2] Hemathilake DM, Gunathilake DM. Agricultural productivity and food supply to meet increased demands. InFuture foods 2022 Jan 1 (pp. 539-553). Academic Press.

[3] Incrocci L, Thompson RB, Fernandez-Fernandez MD, De Pascale S, Pardossi A, Stanghellini C, Rouphael Y, Gallardo M. Irrigation management of European greenhouse vegetable crops. Agricultural Water Management. 2020 Dec 1;242:106393.

[4] Grieve BD, Duckett T, Collison M, Boyd L, West J, Yin H, Arvin F, Pearson S. The challenges posed by global broadacre crops in delivering smart agri-robotic solutions: A fundamental rethink is required. Global Food Security. 2019 Dec 1;23:116-24.

[5] National Academies of Sciences, Division of Behavioral, Social Sciences, Board on Environmental Change, Medicine Division, Nutrition Board, Division on Earth, Life Studies, Water Science, Technology Board, Board on Life Sciences. Science breakthroughs to advance food and agricultural research by 2030. National Academies Press; 2019 Mar 21.
[6] Maksimović M, Omanović-Mikličanin E. Green Internet of things and green nanotechnology role in realizing smart and sustainable agriculture. InVIII international scientific agriculture symposium "AGROSYM 2017 Oct 5 (pp. 2290-2295).
[7] Rayhana R, Xiao G, Liu Z. Internet of things empowered smart greenhouse farming. IEEE journal of radio frequency identification. 2020 Mar 31;4(3):195-211.
[8] Mohamed ES, Belal AA, Abd-Elmabod SK, El-Shirbeny MA, Gad A, Zahran MB. Smart farming for improving agricultural management. The Egyptian Journal of Remote Sensing and Space Science. 2021 Dec 1;24(3):971-81.
[9] Majid M, Habib S, Javed AR, Rizwan M, Srivastava G, Gadekallu TR, Lin JC. Applications of wireless sensor networks and Internet of things frameworks in the industry revolution 4.0: A systematic literature review. Sensors. 2022 Mar 8;22(6):2087.
[10] Klerkx L, Jakku E, Labarthe P. A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS-Wageningen journal of life sciences. 2019 Dec 1;90:100315.
[11] Chamara N, Islam MD, Bai GF, Shi Y, Ge Y. Ag-IoT for crop and environment monitoring: Past, present, and future. Agricultural systems. 2022 Dec 1;203:103497.
[12] Mandal S, Yadav A, Panme FA, Devi KM, SM SK. Adaption of smart applications in agriculture to enhance production. Smart agricultural technology. 2024 Mar 13:100431.
[13] Ball T, de Halleux P, Devine J, Hodges S, Moskal M. Jacdac: Service-based prototyping of embedded systems. Proceedings of the ACM on Programming Languages. 2024 Jun 20;8(PLDI):692-715.
[14] Haq ES, Setiadevi S, Rini EM, Yusuf D, Aji AA. Investigating an Enhanced Approach for Greenhouse Climate Control: Optimising Cooling and Heating Systems. International Journal on Advanced Science, Engineering & Information Technology. 2023 Nov 1;13(6).
[15] Ali A, Hussain T, Tantashutikun N, Hussain N, Cocetta G. Application of smart techniques, internet of things and data mining for resource use efficient and sustainable crop production. Agriculture. 2023 Feb 8;13(2):397.