Development of Wireless Sensor Network Prototype for the Monitoring of an Intelligent Greenhouse

Komalpreet Kaur[1], Mandeep Kaur[1]
[1]*Department of Computer Science Engineering, CT University, Ludhiana- 142024, India*

Abstract- **This study presents the design and deployment of a wireless sensor network (WSN) prototype tailored for real-time environmental monitoring in a smart greenhouse. The system integrates Internet of Things (IoT) technology with an array of sensors to monitor key micro-climate parameters, including temperature, humidity, and light intensity. A graphical user interface (GUI) was developed using styled HTML and JavaScript to facilitate interactive control and data visualization. The GUI dispatches asynchronous HTTP requests in response to user interactions, allowing seamless communication with the server. The system underwent testing in a greenhouse situated in Ludhiana (30.8196° N, 75.5558° E) over selected days in April and May 2025. Environmental data were collected every half hour from 8:00 AM to 6:00 PM, and for entire 24-hour periods in some instances. Analysis of the sensor data showed minimal differences between shaded and unshaded sensor readings, with standard deviation values ranging from 0% to 1.53%. The average deviation over the full 24-hour period was found to be 0.46%, increasing to 0.85% during peak monitoring hours between 8:00 AM and 6:00 PM.**

***Index Terms*— Wireless Sensor Network; Smart Greenhouse; Monitoring; Interactive control**

I. INTRODUCTION

Greenhouses (GH) are specifically constructed enclosed farming structures designed to establish a controlled environment inside them to enhance crop production and protection. This environment is tailored to meet the specific needs of a particular crop [1]. Plant growth is influenced by various atmospheric factors, such as temperature, humidity, vapor pressure deficit, light duration and intensity, and CO_2 levels [2]. Additionally, factors in the soil-root zone, including soil moisture, soil temperature, and the concentration of macro-nutrients, play a significant role in plant growth.

To establish controlled environmental conditions in a traditional greenhouse, the first step towards transforming it into an intelligent greenhouse (IGH) is to monitor the parameters affecting plant growth. In the early stages of IGH development, a single sensor placed in the greenhouse was used to detect the parameter of interest. However, this method did not provide accurate information about the greenhouse's micro-climatic conditions.

Wireless communication has experienced its sharpest growth period in the past few decades, owing to widespread adoption in different devices and technologies of daily use [3]. A Wireless Sensor Network (WSN) consists of numerous battery-powered sensor nodes designed to gather, observe, and transmit environmental data [4]. The sensors communicate wirelessly, transmitting their collected information to a central point for further processing and examination [5]. Each node is a compact device equipped with sophisticated sensing capabilities, a small processor, and a short-range wireless transmitter. These motes form an array that works collectively to monitor and relay data from the surrounding environment [4]. An improvement on the single-sensor monitoring technique involved deploying multiple sensors in conjunction with a data acquisition system to obtain a precise profile of the variables.

An increasing number of researchers are interested in the development of WSNs for numerous applications including defense, health monitoring [6], environmental and industrial applications [7]. The evolution of WSNs has been driven by advancements in communication protocols, energy efficiency, and integration with the Internet of Things (IoT), which enhances their functionality across diverse sectors. A study conducted by Ren et. al. [8] explored the use of mobile sensing in the development of wireless sensor networks, specifically focusing on node placement

planning and in-field calibration. The researchers confirmed the effectiveness of mobile sensing in guiding WSN deployment. In a study by Duobiene et. al. [9], researchers assessed the scalability of industrial wireless sensor networks (IWSNs) and introduced a new classification method for industrial IoT. The approach combines 6LoWPAN, MQTT-SN, and ContikiMAC protocols to enhance energy-efficient connectivity, resulting in a 50% improvement in energy efficiency and a 350% increase in battery lifespan.

Palarimath et. al. [10] investigated the impact of Internet of Things (IoT) technology on Wireless Sensor Networks (WSNs) in the context of Industry 4.0 applications. Kumar et. al. [11] conducted a comprehensive analysis of sensor networks' importance in contemporary applications. Their review examined the operational features of these networks and their capacity to enhance various industries through the collection and analysis of real-time data. Praveena et. al. [12] presented a thorough investigation for monitoring greenhouses using a Wireless Sensor Network (WSN). The research focused on tackling the issues associated with tracking temperature and humidity levels in greenhouses. Healthcare applications of intelligent WSNs were further reviewed by Singh, Kaur, and Malhotra [13], who explored their potential in chronic disease monitoring. Their findings pointed to the usefulness of WSNs integrated with AI for early detection, albeit noting challenges such as power limitations and data privacy.

Akhtar, Ullah, and Ali [14] reviewed energy-efficient routing protocols tailored for smart healthcare systems. Their review underscored how classifiers such as SVM and decision trees optimize applications like disease detection and irrigation, enhancing overall crop management. Security, another vital consideration in healthcare, was addressed by Dinh, Nguyen, and Lee [15], who proposed a lightweight cryptographic scheme using elliptic curve cryptography (ECC). Their solution minimizes computational overhead while maintaining strong data protection, making it especially suitable for wearable medical devices. In agriculture, Li, Zhang, and Wang [16] developed a smart irrigation system powered by a WSN using Zigbee and microcontrollers. The system achieved substantial water savings and improved yield through automated, sensor-based irrigation scheduling. Similarly, Bashir, Azam, and Mahmood [17] implemented a data acquisition system that enabled real-time monitoring of environmental parameters like humidity and soil moisture, aiding precision farming efforts.

Apart from the above-mentioned studies, many other researchers have used WSNs in diverse applications for monitoring of different parameters for greenhouse, disaster management [18], construction sites [19], healthcare and forest fire detection [20] etc. From the review, it was observed that the effect of sensor shading on the effectiveness of monitoring has not been evaluated. Furthermore, it is also very crucial to understand and monitor few outdoor parameters to achieve the required plant growth and inside conditions as per crop requirement. GUI needs to be developed for such WSN which can monitor all these parameters at a single point which can be further integrated with IoT devices to control these parameters wirelessly. Therefore, the focus of this study is to design a wireless sensor network (WSN) for a intelligent greenhouse which will employ multiple sensor nodes for environmental monitoring. The WSN will gather and monitor various micro-climate conditions like temperature, soil moisture level, humidity, luminosity, CO_2 levels etc. inside a greenhouse under shaded/unshaded conditions and will be controlled via a graphical user interface.

II. METHODOLOGY

2.1 System Overview

The greenhouse environment monitoring system is designed to enable remote observation of the conditions inside a greenhouse. An experimental setup consisting a greenhouse prototype model has been developed which has been integrated with programmed control and monitoring units. This system offers real-time readings of selected parameters via Wi-Fi, accessible through a custom-developed GUI. The ESP8266 Wi-Fi Module is integrated with sensors to track environmental conditions within the greenhouse, and this information is then sent to IoT platforms. In the remote-control setup, the ESP8266 NodeMCU is linked to a multi-channel relay that connects to water pumps, humidifiers, grow lights, and windows. Additionally, it is programmed to interact with IoT platforms. User-generated control instructions for the multi-channel

relay are sent to the ESP8266 Wi-Fi Module through IoT platforms, enabling remote operation.

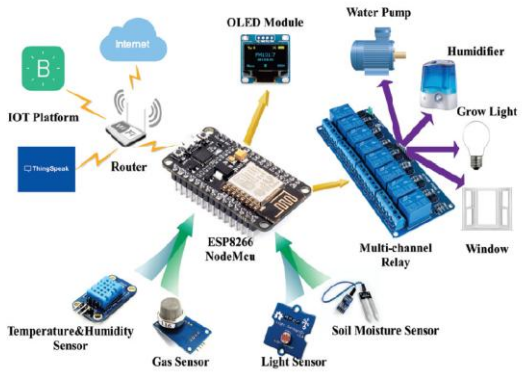
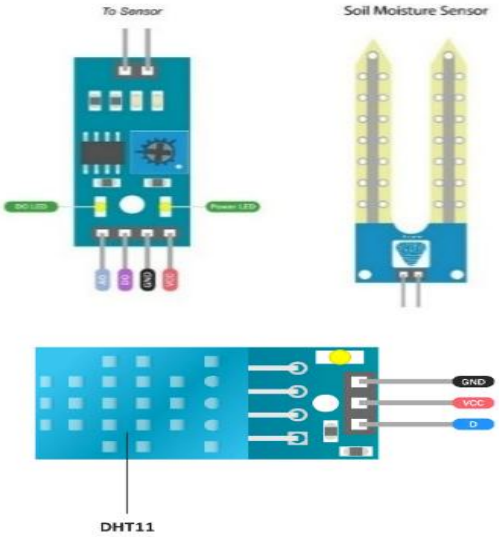


Fig. 1 Overview of the system

2.2 Selection of Sensors

The wireless sensor node which has been developed in this research work has considered five parameters, namely, atmospheric temperature, humidity, luminosity, soil moisture and soil temperature. The LM293 based soil moisture sensor has been used for the measurement of soil moisture level. The working temperature range of LM293 comparator lies between −25°C t o 85°C. The DHT11 temperature and humidity sensor has been utilized to monitor both the parameters. It measures relative humidity and temperature and provides a digital output ranging 0-50°C and 20-90% RH value. In addition to the temperature, humidity and soil moisture, MQ135 gas sensor was selected to measure CO_2 concentration of the air in the interior of the greenhouse.



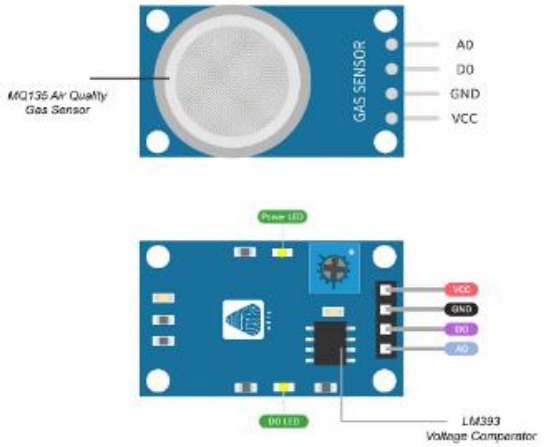


Fig. 2 Pin layout diagram soil moisture sensor, temperature sensor and gas sensor used in present study

2.3 Central Unit:

In the present study, ESP8266 NodeMCU is selected in order to interface with sensor nodes and to upload the environmental data to the IoT platforms though Wi-Fi. Based on the HTTP Protocol, NodeMCU can communicated with IoT platforms and cloud using API Key (Application Program Interface). Hence, users can have access to monitoring and managing their private environmental data which can be observed on the OLED Module and through the developed GUI as well. The pin layout of ESP8266 NodeMCU is shown in Figure 3.

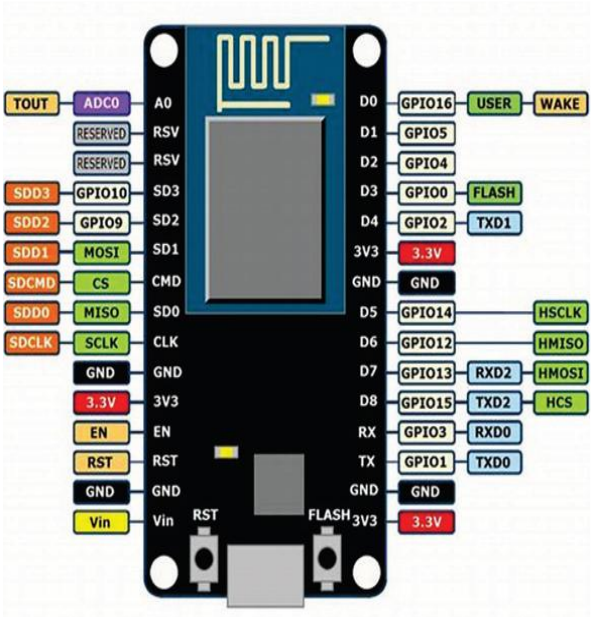


Fig. 3 Pin layout of ESP8266 NodeMCU

2.4 Selection of Nodes and Location:

Three sensors are positioned at equal intervals along the length to capture average values for temperature, humidity, and other parameters. The distance from the door to the sensors and from the sensors to the opposite end is half the distance between each sensor. A schematic diagram illustrating the placement of the sensor nodes is provided in the figure below.

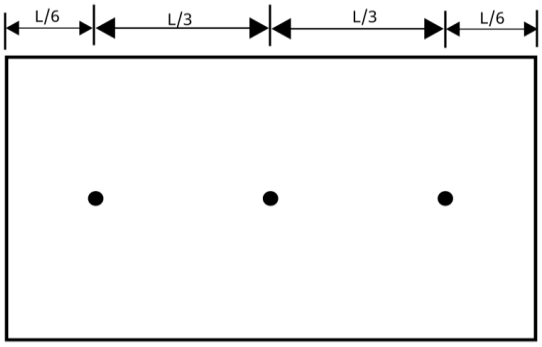


Fig. 4 Placement locations of Sensor nodes inside the greenhouse.

2.5 Development of the WSN Network:

A web interface has been created using HTML and JavaScript to support a wireless sensor network (WSN) node equipped with an ESP32 microcontroller, which is intended to control various relays through a web-based graphical user interface (GUI). The system will connect to a Wi-Fi network and run a non-blocking web server using the ESPAsyncWebServer library. Sensor nodes incorporating multiple sensors and a gateway will be constructed to gather sensor data at a central location for processing and further development. Sensor calibration will also be conducted at this stage. Additionally, data on temperature, relative humidity, and radiation intensity were gathered from the central sensors of the greenhouse's control system. The WSN and portable radiation intensity units collected data every 30 seconds, with averages reported every 2 minutes. These readings were then averaged over 10-minute intervals to align with the greenhouse's central control unit's time-step.

III. RESULTS AND DISCUSSION

3.1 Development of WSN User Control Interface

A web-based interface has been developed using HTML and JavaScript to facilitate a wireless sensor network (WSN) node with an ESP32 microcontroller, aimed at managing eight relays via a graphical user interface (GUI) on the web. The developed programming banks upon gathering data from various installed sensors, including temperature, humidity, solar radiation, and soil moisture. The system links to a Wi-Fi network and operates a non-blocking web server through the ESPAsyncWebServer library. The GUI (Fig. 5) is dynamically created by inserting relay-specific control components through a placeholder mechanism, enabling efficient and scalable relay management.

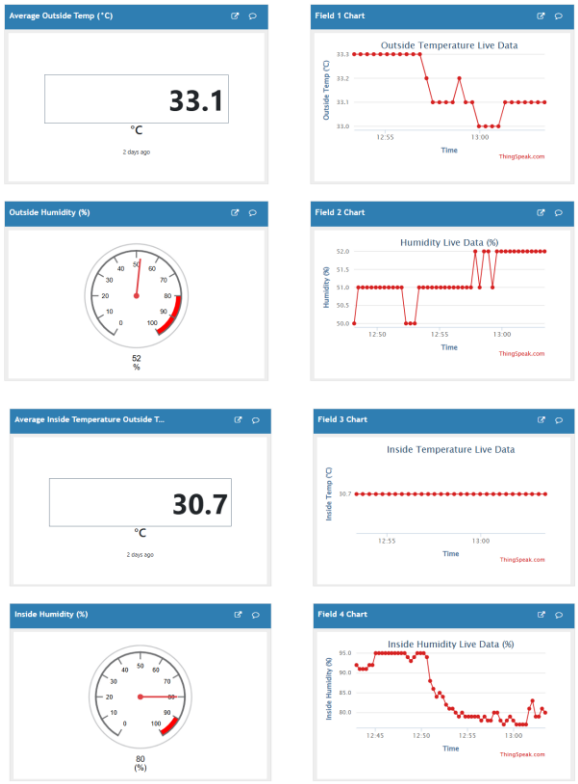


Fig. 5 Real-time greenhouse dashboard for monitoring of different parameters.

3.2 Monitoring of Intelligent greenhouse over a period of time

The data analysis from the monitoring of the Intelligent greenhouse using the developed WSN system are visualized in the graphical and tabular forms obtained from the developed GUI. The data analysis has been done during the selected days for the month of April and May-2025 in Ludhiana (30.8196° N, 75.5558° E). Although the developed WSN provides the live data at every 15 seconds, the analysis has been done at half hour interval from 8:00 am – 6:00 pm and for complete 24-hour period as well for

some parameters as required. The effect of shaded and un-shaded sensor nodes has been developed in this analysis and the outcomes of Sensor 3 (un-shaded) is included in contrast to the Sensor1 and Sensor 2 which are shaded suitably.

Fig. 6 illustrates the real-time inside temperature variations within a greenhouse from 8:00 AM to 6:00 PM on April 12, 2025, as recorded by three temperature sensors. Sensor 1 and Sensor 2 have been shaded from sunlight, while Sensor 3 is left unshaded and exposed to direct sunlight inside the greenhouse.

From the data, it is evident that all sensors show a general upward trend in temperature from morning to early afternoon, peaking around 2:00 to 3:00 PM, followed by a gradual decline towards the evening. Between 8:00 AM and 10:00 AM, the temperature rises sharply as solar radiation increases, with Sensor 3 consistently recording higher temperatures than the shaded sensors due to direct sunlight exposure. The maximum temperature recorded by the unshaded sensor 3 is 43.9°C whereas at the same time shaded sensors reported temperature was 40.7°C.

Throughout the day, Sensor 3 maintains a noticeably higher temperature profile, particularly between 1:00 PM and 4:00 PM, where the difference between Sensor 3 and the shaded sensors (Sensor 1 and Sensor 2) becomes more pronounced. This indicates the significant impact of solar radiation on local micro-climate conditions within the greenhouse and highlights the influence of shading on temperature regulation in greenhouses for accurate environmental monitoring and effective micro-climate control.

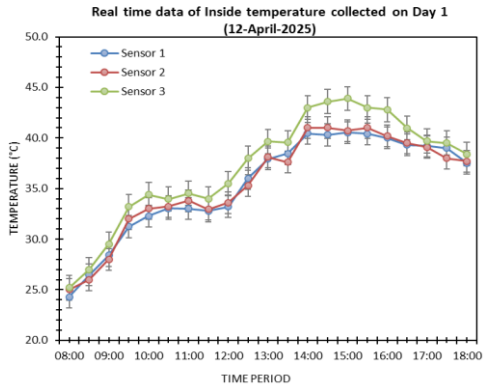


Fig. 6. Real-time inside temperature variations within a greenhouse over a 10-hour period.

In addition to the monitoring of temperature, the humidity levels inside the intelligent greenhouse are also observed with the developed WSN system and monitored through the graphical user interface (GUI). The graphical data analysis is performed at 30-minute intervals from 8:00 AM to 6:00 PM. During this monitoring period, the greenhouse operates under uncontrolled environmental conditions, with no automated systems being used for humidity regulation.

Fig. 7 illustrates the real-time inside humidity levels within a greenhouse from 8:00 AM to 6:00 PM on April 12, 2025, as recorded by three different sensors. Similar to the previous analysis, Sensor 1 and Sensor 2 have been shaded from sunlight, while Sensor 3 is left unshaded and exposed to direct sunlight inside the greenhouse.

From the data, it is evident that all sensors show a general decline trend in the humidity levels from morning to afternoon, followed by a gradual incline towards the evening. Between 8:00 AM and 3:00 PM, the humidity declines sharply. Furthermore, with Sensor 3 being exposed to the direct sunlight, the humidity levels are almost similar or slightly lesser than the other two sensors which are shaded.

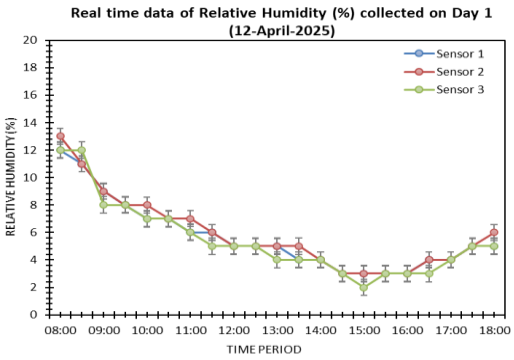


Fig. 7 Real-time humidity levels inside the greenhouse over a 10-hour period.

Fig. 8 illustrates the comparative plot of temperature inside the greenhouse and outside temperature monitored through WSN for a 10-hour period from 8:00 AM – 6:00 PM. The inside temperature of the greenhouse is averaged from the readings of 3 different sensors placed inside. As expected, the temperature sensors show increasing trend till afternoon and afterwards remain flat or slightly decreasing in the evening. In contrast to the outside temperature, the sensors inside the greenhouse shows relatively higher temperature, confirming with the greenhouse effect inside. The effect is lesser in the

morning and much higher in the afternoon when temperature becomes high.

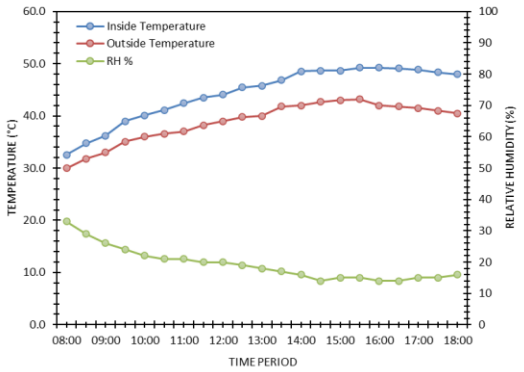


Fig. 8. Comparison of inside temperature, outside temperature and relative humidity levels in the greenhouse over a 10-hour period.

IV. CONCLUSIONS

In the present study, a system was developed using IoT and different sensors which can gather real-time micro-climate data—such as temperature, humidity, and light levels—to aid precision farming and boost crop yields. Furthermore, the system incorporates a graphical user interface (GUI) to enable real-time visualization and monitoring of environmental parameters, allowing users to make informed decisions based on the gathered data. Based on the findings of the study, following major conclusions are drawn:

1. A real time WSN framework has been developed which employs styled HTML and JavaScript to dispatch asynchronous HTTP requests to the server.
2. A subsequent system is developed to establish an interface that allows the ESP32 microcontroller for interacting with various sensors and transmitting the gathered data to the ThingSpeak cloud platform for remote observation.
3. The live wireless monitoring of the greenhouse has been achieved for the selected days for the month of April and May-2025 in Ludhiana (30.8196° N, 75.5558° E). The analysis has been done at half hour interval from 8:00 am – 6:00 pm and for complete 24-hour period as well for some parameters as required.
4. The standard deviation of the sensor values reported by the shaded and unshaded sensors with respect to the solar radiation levels over a 24-hour period. It can be seen that the deviation is of the order 0-1.53% throughout the day.
5. The average deviation of the sensor values during the entire 24-hour period is 0.46 % and the average deviation during the selected 10-hour period from 8:00 AM–6:00 PM is 0.85%.

REFERENCE

[1]. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: A survey. *Computer Networks, 38*(4), 393–422.

[2]. Dargie, W., & Poellabauer, C. (2010). *Fundamentals of wireless sensor networks: Theory and practice*. Wiley.

[3]. Ávila, B. Y. L., Vázquez, C. A. G., Baluja, O. P., Cotfas, D. T., & Cotfas, P. A. (2025). Energy harvesting techniques for wireless sensor networks: A systematic literature review. *Energy Strategy Reviews*, *57*, 101617.

[4]. Sahu, M., & Victor, V. M. (2025). Enhancing Agriculture through Wireless Sensor Networks. *International Journal of Environment and Climate Change*, *15*(1), 94-103.

[5]. Adday, G. H., Subramaniam, S. K., Zukarnain, Z. A., & Samian, N. (2024). Investigating and analyzing simulation tools of wireless sensor networks: a comprehensive survey. *IEEE Access*, *12*, 22938-22977.

[6]. Kumar, H. (2024). Wireless sensor networks in healthcare system: A systematic review. *Wireless Personal Communications*, *134*(2), 1013-1034.

[7]. Majid, M., Habib, S., Javed, A. R., Rizwan, M., Srivastava, G., Gadekallu, T. R., & Lin, J. C. W. (2022). Applications of wireless sensor networks and internet of things frameworks in the industry revolution 4.0: A systematic literature review. *Sensors*, *22*(6), 2087.

[8]. Ren, J., Li, Z., Cao, X., & Kong, X. (2025). Experimental study on the application of mobile sensing in wireless sensor networks development: Node placement planning and on-site calibration. *Sensors and Actuators B: Chemical*, 137338.

[9]. Duobiene, S., Simniškis, R., & Račiukaitis, G. (2024). *Enabling Seamless Connectivity: Networking Innovations in Wireless Sensor Networks for Industrial Application*. *24*.

[10]. Palarimath, S., Pyingkodi, M., N.R, W. B., Sujatha, T., Renuga, S., & R.S, C. (2024). *Exploring the Role of Internet of Things in Wireless Sensor Networks for Industry 4.0 Applications*. 616–621.

[11]. Kumar, R., Sharma, S. K., & Singh, R. (2022). Precision agriculture using wireless sensor networks and machine learning: A review. *Computers and Electronics in Agriculture, 200*, 107082.

[12]. Praveena, M., Babiyola, A., Aghalya, S., & Sasikar, A. (2023). *Wireless Sensor Network Based Greenhouse Monitoring Using Cloud Integration with Data Analytics*. 68–72.

[13]. Singh, D., Kaur, M., & Malhotra, J. (2023). Intelligent wireless sensor systems for chronic disease detection: Opportunities and challenges. *Biomedical Signal Processing and Control, 80*, 104343.

[14]. Akhtar, N., Ullah, S., & Ali, S. (2023). Energy-efficient routing protocols for WSN-based smart healthcare systems: A review. *IEEE Access, 11*, 10245–10261.

[15]. Dinh, H. C., Nguyen, T. A., & Lee, Y. K. (2021). A lightweight and secure communication scheme for healthcare WSNs using elliptic curve cryptography. *Sensors, 21*(5), 1682.

[16]. Li, H., Zhang, L., & Wang, Y. (2020). A wireless sensor network-based irrigation management system for smart farming. *Sensors, 20*(4), 1221.

[17]. Bashir, F., Azam, F., & Mahmood, A. (2021). WSN-based data acquisition for environmental monitoring in smart agriculture. *Journal of Sensor and Actuator Networks, 10*(2), 34.

[18]. Pant, D., Verma, S., & Dhuliya, P. (2017, September). A study on disaster detection and management using WSN in Himalayan region of Uttarakhand. In *2017 3rd International conference on advances in computing, communication & automation (ICACCA)(Fall)* (pp. 1-6). IEEE.

[19]. Shen, X., Cheng, W., & Lu, M. (2008). Wireless sensor networks for resources tracking at building construction sites. *Tsinghua Science and Technology*, *13*(S1), 78-83.

[20]. Pedditi, R. B., & Debasis, K. (2023). Energy efficient routing protocol for an IoT-based WSN system to detect forest fires. *Applied Sciences*, *13*(5), 3026.