



An IoT-Enabled Intelligent Greenhouse Management System for Sustainable Agriculture

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Abstract: Conventional greenhouse farming depends heavily on manual supervision to regulate ambient microclimates, often leading to sub-optimal yields, resource mismanagement and high labor costs. This paper presents an Internet of Things (IoT)-driven smart greenhouse monitoring and closed-loop control system utilizing a coordinated dual-microcontroller architecture (ATmega328P Arduino Uno and ESP8266 Node MCU). The system continuously samples ambient temperature and relative humidity by DHT22 sensor, air quality index (AQI) by MQ135 sensor and irrigation management by using soil moisture sensors. Data is locally displayed on LCD and transmitted over Wi-Fi to the Blynk IoT cloud platform. Automated actuation controls a submersible DC water pump for threshold-based irrigation, an exhaust fan for thermo-hygrometric regulation, an SG90 servo-actuated ventilation triggered by excessive gas and IR-based automated gate control by the servo motor. An automated cloud-triggered email notification system delivers audible push alerts to mobile end-users during anomalous threshold breaches.

Key Words: IoT, Smart Greenhouse, ESP8266 Node MCU, Arduino Uno, Precision Agriculture, Blynk IoT

I. INTRODUCTION

Agriculture plays a vital role in the economy, but traditional farming methods are highly dependent on climatic conditions and manual monitoring which frequently results in uneven crop yields and wasteful resource consumption. Plant growth and production are significantly influenced by variables like temperature, humidity, light intensity, soil moisture and soil pH. Maintaining these parameters manually inside a greenhouse is time-consuming, labor-intensive, and prone to human error. With the advancement of Internet of Things (IoT) technology, it has become possible to continuously monitor environmental conditions and automatically control them in real time. A smart greenhouse system integrates sensors, actuators, and cloud-based platforms to create an optimal environment for plants with minimal human intervention^{1,2,3}. The primary objective of this project is to design and develop an IoT-Based Smart Greenhouse Monitoring and Control System^{4,5} capable of continuously monitoring critical environmental parameters and automatically controlling various greenhouse operations to provide an optimal environment for plant growth. The proposed system aims to reduce human intervention, improve resource utilization, and increase agricultural productivity through real-time sensing, intelligent automation, cloud-based monitoring and automated irrigation to improve agricultural productivity and sustainability.

This proposed work on IoT-Based Smart Greenhouse Monitoring and Control System is an automated precision-agriculture platform centered on the ESP8266 NodeMCU, which performs sensor interfacing, threshold-based decision-making, actuator control, and wireless data transmission. The system employs a DHT22 sensor for ambient temperature and relative humidity, a soil-moisture sensor for irrigation assessment, an MQ135 sensor for air-quality monitoring. Based on predefined environmental thresholds, the ESP8266 automatically controls the corresponding actuators, including the irrigation system, exhaust fan, and servo-operated ventilation mechanism, thereby maintaining suitable conditions for plant growth. An IR sensor additionally enables automatic operation of the greenhouse entrance gate through a servo motor. A 16×2 LCD with an I²C interface provides real-time local visualization of the monitored parameters, while Wi-Fi connectivity enables remote data monitoring through the Blynk IoT Cloud platform. The resulting closed-loop architecture integrates environmental sensing, real-time processing, automated actuation, and cloud-based monitoring, providing a modular and scalable framework for greenhouse automation with scope for future integration of AI/ML-based predictive control, advanced analytics, renewable energy, and large-scale deployment.

II. LITERATURE SURVEY

In the last decade, significant research has been conducted on IoT-based greenhouse monitoring and automation systems to overcome the limitations of traditional manual greenhouse management. Many studies have focused on monitoring individual environmental factors and automating one or more control mechanisms. Navulure *et al.*⁶ and S. Kumar & P. Tiwari⁷ explored basic single-microcontroller (e.g., Arduino Uno or ESP8266) systems to automate water pumps and exhaust fans based on DHT11 and soil moisture data. Wang *et al.*¹ discussed the application and development of wireless sensor technologies in agriculture to monitor continuously without requiring physical presence at the cultivation site. Burrell *et al.*² investigated the use of sensor networks in agricultural production and demonstrated the potential of networked sensing for collecting environmental information from agricultural environments. Ruiz-Garcia *et al.*³ presented a comprehensive review of wireless sensor technologies and their applications in agriculture and food industries. Further studies integrated fuzzy logic⁵ or explainable AI models to refine multi-variable climate control, utilizing IoT dashboards such as ThingSpeak and Blynk. Subsequent research has increasingly combined IoT communication with embedded controllers and cloud platforms. Navulure *et al.*⁶ discussed agricultural management through wireless sensors and IoT, demonstrating the potential of connected sensing systems for agricultural monitoring. More recent research has explored artificial intelligence and machine-learning techniques for agricultural decision-making. Kamilaris and Prenafeta-Boldú⁵ reviewed deep-learning applications in agriculture and highlighted the potential of AI for crop monitoring, prediction and agricultural automation⁸.

The novelty of the proposed IoT-based Smart Greenhouse System lies in its integrated multi-parameter sensing and coordinated automated control within a single ESP8266-based platform. Unlike conventional systems that monitor limited environmental parameters or operate actuators independently, the proposed system uses two microcontrollers and simultaneously monitors temperature, humidity, soil moisture, and air quality (AQI) and uses multi-parameter decision logic to control exhaust fans, servo-operated ventilation windows, and heating mechanisms. The incorporation of real-time Blynk-based remote monitoring, and automatic email alerts for threshold violations further enhances energy efficiency, environmental stability, responsiveness, and practical usability.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

The proposed IoT-Based Smart Greenhouse Monitoring and Control System is designed to monitor and automatically control important greenhouse environmental parameters. The system uses two microcontrollers: Arduino Uno for sensor data acquisition and local control, and ESP8266 NodeMCU for IoT connectivity and remote monitoring. The system uses DHT22, MQ135 and soil moisture sensors to measure temperature, humidity, air quality and soil moisture. The sensor data are collected by the Arduino Uno and compared with predefined threshold values. Based on these values, the Arduino controls different actuators, including a DC water pump, exhaust fan, relay module, and SG90 servo motor, to perform automatic irrigation, ventilation, and gate control. The relay module is used to control the DC water pump and exhaust fan according to the predefined environmental threshold conditions. The water pump is activated when the soil moisture level falls below the specified threshold, while the exhaust fan is operated when ventilation is required. The SG90 servo motor is used to control the greenhouse gate or ventilation mechanism automatically. The IR sensor provides the input required for automatic gate operation. A 16×2 LCD with I²C interface displays the measured environmental parameters locally in real time. The Arduino Uno communicates with the ESP8266 NodeMCU through serial communication. The processed sensor data are also transferred to the ESP8266 NodeMCU, which connects to the Blynk IoT platform through Wi-Fi for remote monitoring. When any monitored parameter exceeds its predefined threshold, the ESP8266 generates an email alert to notify the user about the abnormal environmental condition. Thus, the proposed system integrates sensor-based monitoring, automatic control, IoT connectivity, and real-time alerts to provide efficient greenhouse management with reduced human intervention.

The methodology of the whole proposed work has been described in the given block diagram.

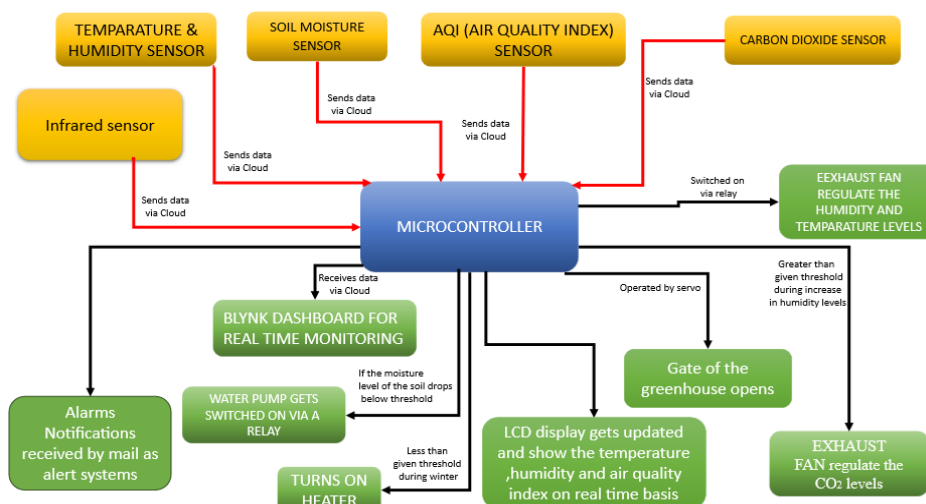


Fig. 1: Functional Architecture of the IoT-based smart greenhouse system

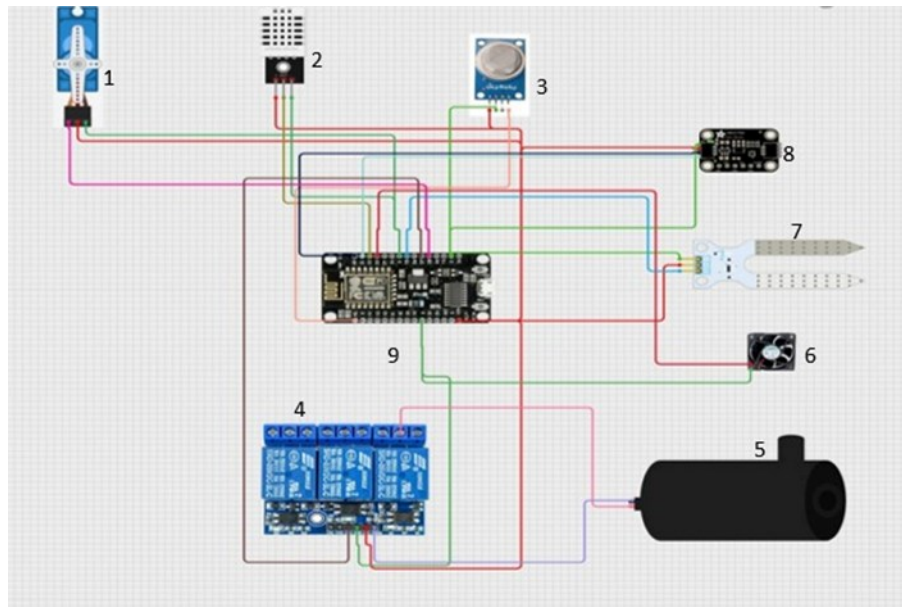


Fig. 2: Circuit diagram of IoT-Based Smart Greenhouse Monitoring and Control System

The label components used in this circuit diagram are 1) Servo motor 2) DHT22 sensor 3) MQ-135 sensor 4) 3 channel Relay module 5) 12V water pump 6) 12V Exhaust Fan 7) Soil moisture sensor 8) Heater and 9) ESP-8266 NodeMCU.

Working Principle:

- 1) Multi-parameter monitoring:** The prototype combines DHT22 temperature/humidity sensing, MQ135 air-quality sensing and soil-moisture measurement monitoring.
- 2) Automatic irrigation:** The documented Arduino logic treats an analog soil-moisture reading of 800 or above as a dry condition and switches the pump through a relay. When the reading reaches 500 or below, the pump is switched off. The use of separate start and stop limits reduces rapid relay oscillation and provides a simple form of control hysteresis on the sensor's 0–1023 analog scale.
- 3) Thermal and humidity regulation:** The documented ESP8266 control program starts the exhaust system when temperature reaches 35 °C or humidity reaches 75%. The fan is released only when temperature falls below 35 °C and humidity falls to 68% or lower. The different ON and OFF limits reduce frequent switching near the threshold.
- 4) Automated ventilation:** The prototype uses an SG90 servo motor with the IR-based gate automation mechanism to operate the greenhouse ventilation gate/window.
- 5) Local and remote observability:** The LCD output and Blynk dashboard provide two complementary monitoring paths. Local visualization supports commissioning and troubleshooting, while cloud visualization supports remote supervision.
- 6) Alert responsiveness:** The captured notification output demonstrates that abnormal conditions can be communicated remotely. This reduces dependence on continuous manual observation and provides an additional response channel.

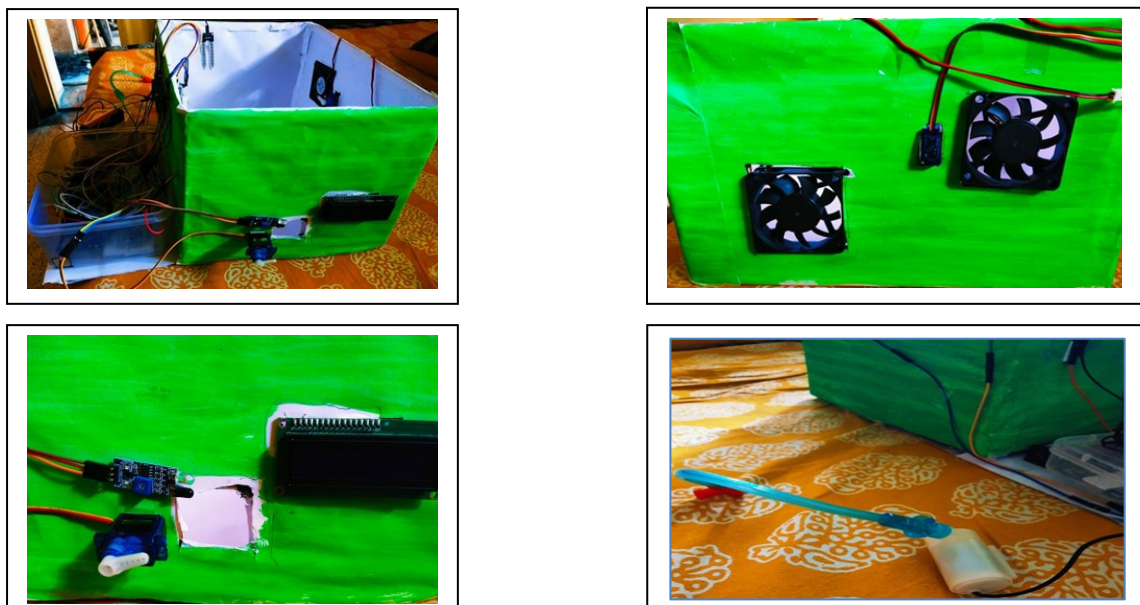


Fig. 3: IoT-Based Smart Greenhouse Monitoring and Control System with Exhaust Fans, and Water Pump.

IV. RESULTS AND DISCUSSION

The proposed IoT-Based Smart Greenhouse Monitoring and Control System was successfully implemented and tested to verify its functionality under different environmental conditions. The developed prototype effectively monitored the essential greenhouse parameters, including temperature, humidity, soil moisture, air quality and performed automatic control operations like irrigation, ventilation and the greenhouse gate based on predefined threshold values. The experimental outputs demonstrate that the system continuously acquires sensor data and processes it using the Arduino Uno. The processed information is transmitted to the ESP8266 NodeMCU, which uploads the data to the Blynk IoT platform through a Wi-Fi connection. As a result, users can remotely monitor all environmental parameters in real time using the Blynk mobile application.

Figure 4 shows the Blynk IoT dashboard displaying real-time greenhouse parameters such as temperature, humidity, soil moisture and air quality (AQI). The dashboard provides a user-friendly interface for monitoring the greenhouse environment from any location with internet connectivity. Whenever any monitored parameter exceeds its predefined threshold, the ESP8266 automatically generates an email notification, allowing the user to take appropriate corrective action without continuously monitoring the application. Figure 5 shows the actual values of Temperature, Humidity, AQI from Blynk IoT platform for any particular time. The experimental tested values and corresponding controlling operations has been illustrated in Table 1.

Table 1: Experimental Test Conditions and Control Logic

Parameter / Event	Documented condition	Expected actuator response	Observed/verified output
Temperature	$T \geq 30.3^{\circ}\text{C}$	Exhaust fan ON; ventilation response enabled	Functional control implemented
Humidity	$\text{RH} \geq 75\%$	Exhaust fan ON	Functional control implemented
Fan release	$T < 35^{\circ}\text{C}$ and $\text{RH} \leq 68\%$	Exhaust fan OFF	Hysteresis-based release implemented
Soil moisture	Analog value ≥ 800 (dry)	Relay/pump ON	Automatic irrigation logic implemented
Soil moisture recovery	Analog value ≤ 500 (wet)	Relay/pump OFF	Automatic irrigation cut-off implemented
Remote monitoring	Sensor data available	Blynk dashboard updated	Real-time dashboard output documented
Abnormal condition	Any monitored parameter crosses threshold	Notification generated	Email alert output documented

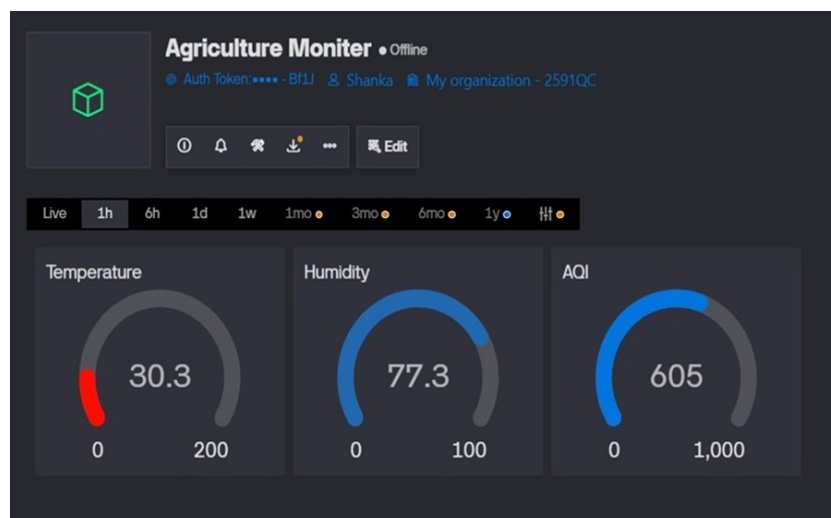


Fig. 4: Real-time Blynk IoT dashboard used for remote greenhouse monitoring

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15:35:17.841 -> Smart Agriculture + Auto Door System Started
15:35:17.908 -> Soil Moisture Value: 12
15:35:17.941 -> IR Sensor Value: 0
15:35:17.941 -> Object Detected!
15:35:17.973 -> Gate OPEN
15:35:20.923 -> Gate CLOSED
15:35:20.954 -> -----
15:35:21.921 -> Soil Moisture Value: 0
15:35:21.954 -> IR Sensor Value: 0
15:35:21.954 -> Object Detected!
15:35:21.990 -> Gate OPEN
15:35:24.929 -> Gate CLOSED
15:35:24.961 -> -----
15:35:25.956 -> Soil Moisture Value: 10
15:35:25.956 -> IR Sensor Value: 0
15:35:25.988 -> Object Detected!

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15:58:53.573 -> Temperature: 30.30 °C | Humidity: 76.70 % | A
15:58:53.752 -> Air Quality: POOR
15:58:53.752 -> -----
15:58:55.544 -> Temperature: 30.30 °C | Humidity: 76.70 % | A
15:58:55.771 -> Air Quality: POOR
15:58:55.771 -> -----
15:58:57.577 -> Temperature: 30.30 °C | Humidity: 76.70 % | A
15:58:57.752 -> Air Quality: POOR
15:58:57.752 -> -----
15:58:59.566 -> Temperature: 30.30 °C | Humidity: 76.70 % | A
15:58:59.766 -> Air Quality: POOR
15:58:59.766 -> -----
15:59:01.544 -> Temperature: 30.30 °C | Humidity: 76.70 % | A
15:59:01.758 -> Air Quality: POOR
15:59:01.758 -> -----
15:59:03.568 -> Temperature: 30.30 °C | Humidity: 76.70 % | A

```

Fig. 5: Actual values of Temperature, Humidity, AQI from Blynk IoT platform

Local LCD Monitoring

Figure 6 depicts the real-time readings displayed on the 16×2 LCD interfaced with the Arduino Uno through the I²C communication module. The prototype reports documents continuously by updating LCD enabling on-site monitoring even when internet connectivity is unavailable. Local visualization is useful during testing and also provides an operating indication when cloud access is temporarily unavailable. The use of the I²C interface reduces wiring complexity by utilizing only two communication lines while ensuring efficient data transmission between the Arduino and the display.



Fig. 6. Prototype LCD output showing real-time environmental parameters

Remote Alert and Notification Response

Figure 7 illustrates the email alert received by the registered user during an abnormal operating condition. The notification contains information indicating that one or more environmental parameters have exceeded the permissible limit, thereby informing the user that immediate attention may be required. As soon as the email is received, the user's smartphone or computer generates a notification sound, providing an additional audible alert even when the Blynk application is not actively being monitored. The successful generation and delivery of the email notification demonstrate the effectiveness of the IoT communication module and verify the proper integration between the Arduino Uno, ESP8266 NodeMCU, and cloud-based notification service. This feature significantly improves the responsiveness of the proposed system by enabling users to take timely corrective action from any remote location with internet access. Consequently, the alert notification mechanism enhances the overall reliability, safety, and automation capability of the smart greenhouse monitoring system.

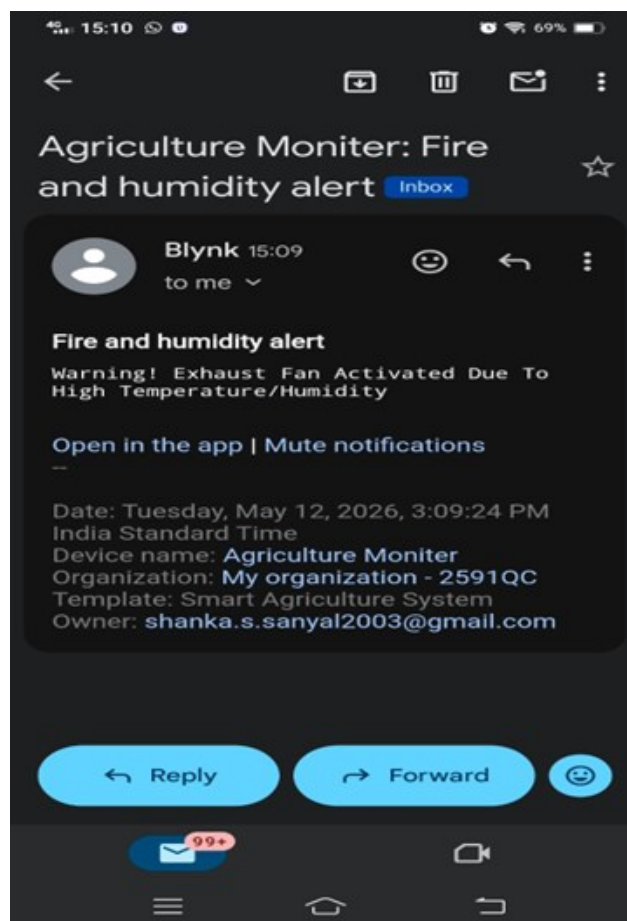


Fig.7. Remote alert notification generated during abnormal operating conditions.

V.CONCLUSION

The proposed IoT-Based Smart Greenhouse Monitoring and Control System was successfully designed and implemented using Arduino Uno and ESP8266 NodeMCU to provide real-time environmental monitoring, automated control, cloud-based visualization, and remote alert notification. The system effectively monitors temperature, humidity, soil moisture, air quality, and autonomously controls irrigation, ventilation, and greenhouse access based on predefined threshold conditions. Experimental validation demonstrates reliable real-time operation and effective integration of low-cost sensors, embedded controllers, and the Blynk IoT platform. The developed prototype therefore offers a cost-effective, scalable, and practical solution for reducing manual intervention, optimizing resource utilization, and supporting precision greenhouse agriculture, while providing a suitable platform for future integration of artificial intelligence and predictive analytics.

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