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RESEARCH ARTICLE

Design and Implementation of an Automated Greenhouse Prototype for Microclimate Regulation Using Arduino and Low-Cost Sensors

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ABSTRACT

Climate variability, resource limitations, and the need for sustainable intensification increasingly threaten agricultural productivity. Traditional farming systems are often labor-intensive and inefficient at managing critical parameters such as temperature, humidity, and soil moisture. In response, this study presents the design and development of a compact and cost-effective smart greenhouse prototype integrated with Internet of Things (IoT) technology to enable automated environmental monitoring and control. The structure is built using an even span design and covered with transparent plastic sheeting to maintain internal conditions while allowing sufficient sunlight penetration. The system incorporates a microcontroller that collects and processes real-time data from various sensors, including those monitoring temperature, humidity, soil moisture, carbon dioxide levels, and light intensity. Based on these readings, the system autonomously operates actuators such as exhaust and intake fans, a water pump, grow lights, and a humidifier to maintain optimal growing conditions. Power is supplied through a battery charged by a solar panel, ensuring energy efficiency and off-grid operation. A liquid crystal display provides real-time feedback on environmental parameters. Field-level testing demonstrated the system's effectiveness in maintaining stable microclimatic conditions suitable for a variety of vegetable and horticultural crops, including tomato. The prototype significantly reduced the need for manual intervention and optimized water and energy usage, aligning with the principles of precision agriculture. The proposed system offers a scalable, environmentally sustainable solution for smallholder farmers, urban growers, and educational applications, thereby enhancing agricultural efficiency and food security.

Keywords: *Greenhouse, Internet of Things, Arduino, Automation, Precision agriculture*

INTRODUCTION

Agricultural systems are under increasing pressure to deliver higher productivity while addressing resource constraints, climate variability, and environmental sustainability. Conventional farming

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practices, especially in open-field conditions, are often inefficient at managing essential parameters such as soil moisture, temperature, humidity, and light intensity, which directly impact plant growth and yield. Moreover, traditional methods require constant manual monitoring and labor, making them unsuitable for precision agriculture or climate-resilient farming systems (Ali *et al.*, 2024; Shamshiri *et al.*, 2018). In recent years, the use of technology in agriculture has significantly increased, particularly with the rise of automation and Internet of Things (IoT) based systems (Patil and Kale, 2016; Mohanraj *et al.*, 2016).

Greenhouse cultivation offers a controlled environment for year-round crop production and mitigates challenges posed by unpredictable weather. However, conventional greenhouses still require frequent human intervention and are often energy- and water-intensive (Thomopoulos *et al.*, 2024). With the advent of digital technologies, the integration of IoT and automation in greenhouse systems has gained momentum. IoT enables real-time environmental sensing, data-driven decision-making, and automated actuation of ventilation, irrigation, lighting, and humidity control systems (Akpulonu *et al.*, 2024; Sujin *et al.*, 2021). As digital farming technologies evolve, integrating IoT and automation into field and greenhouse environments has become essential for increasing efficiency and minimizing resource use (Zalavadiya, 2024). This shift supports the principles of precision agriculture, helping farmers enhance productivity while reducing input costs and resource wastage. Various studies have shown that real-time sensor networks in greenhouses improve yield prediction, climate control, and reduce manual intervention (Abioye *et al.*, 2020).

Despite advancements, many smart greenhouse solutions remain expensive, complex, or unsuitable for smallholders and urban growers. There is a need for low-cost, energy-efficient, and scalable systems tailored to Indian conditions. In this study, we present the design and development of a compact, solar-powered smart greenhouse prototype using IoT-based automation. The system is designed to monitor and control key environmental parameters with minimal manual intervention, using an Arduino-based microcontroller, sensors, and actuators. The aim is to demonstrate a feasible, resource-efficient solution suitable for small-scale farming and educational applications.

MATERIALS AND METHODS

Greenhouse Structure and Design

A small-scale even-span greenhouse was fabricated using 3 mm-diameter mild steel rods to form a lightweight yet durable frame. The structure measured 56 cm in length, 46 cm in width, and 28 cm in sidewall height, with a central peak of 42 cm and a roof angle of 31 °. The 31° roof angle was selected based on standard recommendations for tropical regions, as it optimizes solar light interception, particularly during winter, and facilitates effective rainwater runoff. The frame was covered with a transparent polyethylene sheet to allow natural light while retaining heat and humidity. A wooden baseboard was used for foundational support and to insulate the system from ground moisture. This compact design was chosen for ease of setup in small spaces such as terraces or backyards, targeting applications for urban farmers, smallholders, and institutional demonstration. The structural dimensions and internal layout of the model are illustrated in Figure 1.

Electronic Components and Sensors

An Arduino Uno microcontroller served as the main control unit, processing sensor inputs and activating actuators based on programmed logic. The different sensors were connected to the Arduino via analog and digital pins, using jumper wires and a breadboard for prototyping the circuit (Mohanraj *et al.*, 2016; Abioye *et al.*, 2020).

Actuators and Automation System

Environmental conditions were automatically controlled using the following actuators. All actuators were connected to a 5V 8-channel relay module, allowing isolated control from the Arduino.

- Water Pump (12V): Automates irrigation based on soil moisture threshold.
- Exhaust Fan (12V): Activates when temperature exceeds 27 °C.
- Two Intake Fans (12V): Provide cross-ventilation when temperature exceeds 35 °C.
- USB Humidifier (5V): Operates when relative humidity drops below 50 %.
- LED Grow Lights (5V): Triggered by low light intensity detected by the LDR.

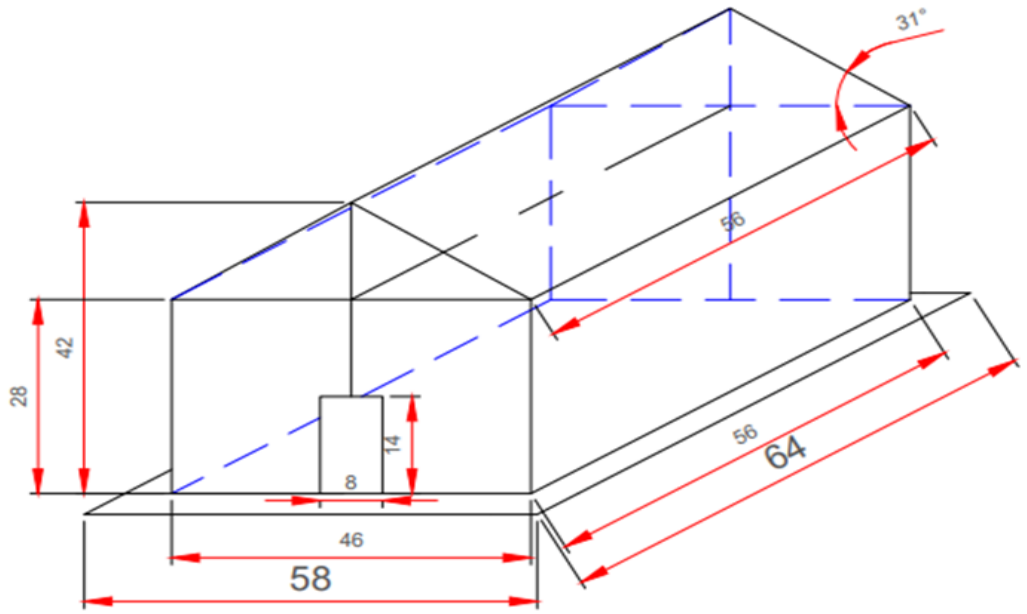


Figure 1. Schematic layout of the greenhouse with dimensions in cm

- Buzzer (Alert System): Activates under abnormal conditions such as high temperature (>40 °C) or very low soil moisture.

The overall system architecture integrating sensors, control unit, relay module, actuators, and power supply components is illustrated in Figure 2.

Power Supply System

The system was designed for off-grid use with renewable energy. A 12V 7.5Ah sealed lead-acid battery powered all components. A 12V solar panel charged the battery. A DC-DC buck converter (LM2596) stepped down the voltage to 5V for sensors, relays, and the Arduino. Wiring connections included male-to-male and female-to-female jumper wires depending on the interface.

Programming and Software Implementation

The system was coded using the Arduino Integrated Development Environment (IDE). Pre-built libraries were imported to simplify sensor integration. Logic was implemented using if statements that activated actuators based on real-time sensor readings, as illustrated in Figure 3.

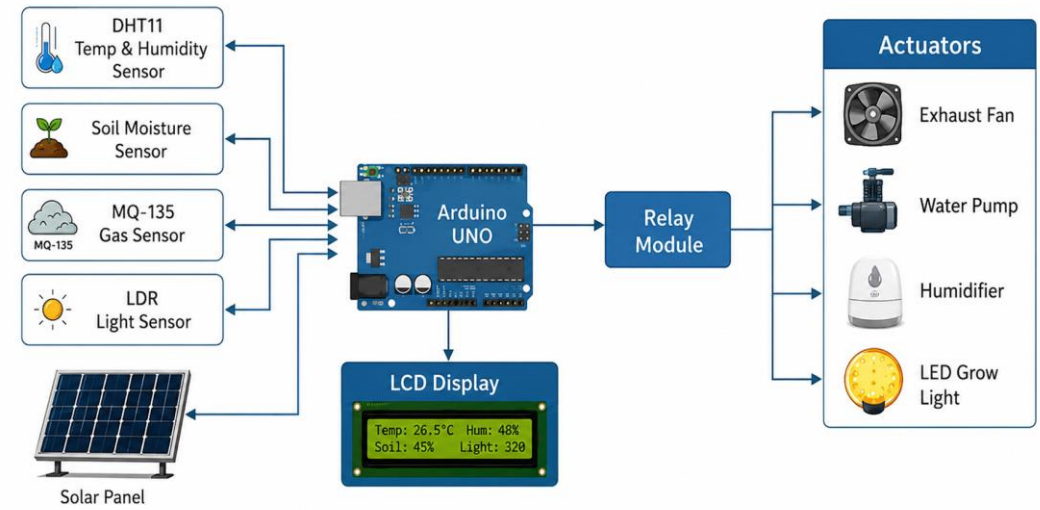


Figure 2. Block diagram of the IoT-based smart greenhouse system architecture

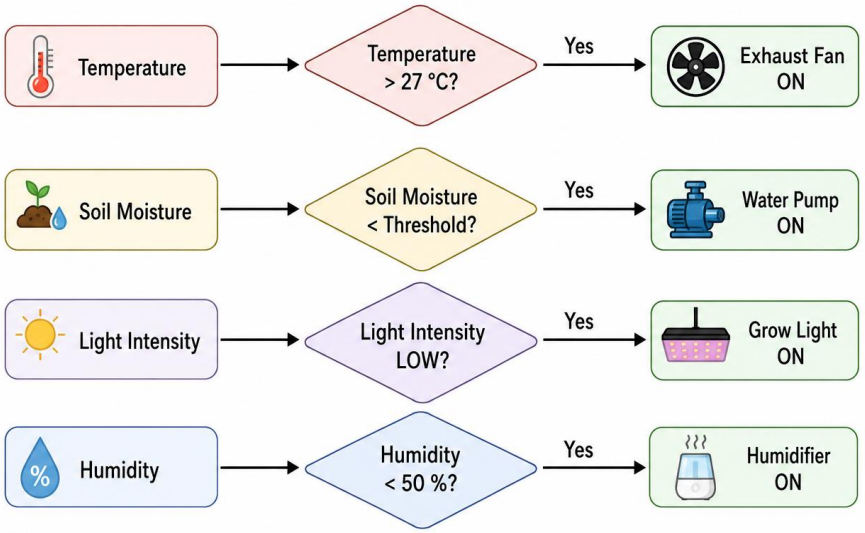


Figure 3. Automated Greenhouse Control Logic Based on Sensor Threshold Conditions

A 16×2 LCD (I2C interface) was included to provide live updates of temperature, humidity, and soil moisture. The fully assembled system was tested for stable operation and correct sensor-actuator response under real conditions. The hardware elements integrated through the Arduino platform, including sensors, relays, display modules, and power units, are summarized in Table 1, along with their specifications and functions.

RESULTS AND DISCUSSION

System Functionality and Sensor Performance

The smart greenhouse prototype was tested under real-world environmental conditions over multiple daytime cycles to evaluate its automation efficiency. All sensors responded accurately within their expected thresholds. The DHT11 sensor measured ambient temperature and humidity, triggering the exhaust fan when the internal temperature exceeded 27 °C and activating both the exhaust and intake fans when it exceeded 35 °C. The humidity-based control successfully activated the USB humidifier when relative humidity dropped below 50%, maintaining suitable conditions for seedling growth and minimizing moisture loss. The soil moisture sensor activated the irrigation system (submersible pump) when soil

Table 1. Components used with specifications and functions

Component	Specification / Model	Function
Arduino Uno	ATmega328P	Main controller
DHT11 Sensor	Temperature & Humidity	Environment monitoring
Soil Moisture Sensor	YL-69 with LM393	Irrigation control
MQ-135 Gas Sensor	CO_2 monitoring	Air quality control
LDR	Light-dependent resistor	Light detection
LCD Display	16×2 with I2C	Parameter display
Relay Module	5V 8-Channel	Actuator control
Water Pump	12V Submersible	Automated irrigation
Exhaust/Intake Fans	12V	Ventilation
Grow Lights	LED strips (5V)	Supplement light
Humidifier	USB-powered (5V)	Humidity regulation
Solar Panel	12V	Renewable power source
Battery	12V, 7.5Ah Lead-Acid	Power storage
Buck Converter	LM2596	Voltage regulation

moisture fell below the preset threshold, ensuring timely watering. This avoided overwatering and demonstrated water-use efficiency, both of which are crucial in precision agriculture. Similarly, the LDR sensor controlled grow light activation during low-light conditions (typically in the evening or on cloudy days), supporting continuous photosynthetic activity for the selected crops. To quantitatively evaluate the effectiveness of the automated control system, the observed environmental parameters were summarized against their predefined threshold values. The stabilization performance achieved during testing cycles is presented in Table 2.

The results indicate that the system maintained environmental parameters within acceptable ranges, demonstrating stable microclimate regulation. The fully assembled and operational prototype is shown in Figure 4, demonstrating the integration of all control, sensing, and actuation components.

Statistical Evaluation of Environmental Stability

To further assess the reliability and consistency of the automated greenhouse system, statistical analysis of key environmental parameters was conducted. Descriptive statistics, including mean, standard deviation (SD), and coefficient of variation (CV), were calculated from recorded observations across multiple operational cycles. The statistical summary of recorded parameters is shown in Table 3.

The low coefficient of variation (<10 %) indicates stable microclimate regulation and consistent actuator response under automated control. Additionally,

Table 2. Microclimate Control Performance under Automated Operations

Parameter	Set Threshold	Observed Range	Control Action	Stability Achieved (%)
Temperature (°C)	27–35	26.8–34.6	Exhaust + Intake Fans	92 %
Relative Humidity (%)	>50	48–68	Humidifier	88 %
Soil Moisture (%)	Threshold-based	Maintained within optimal	Pump	90 %
Light Intensity	Low detection	Artificial supplementation	LED	95 %

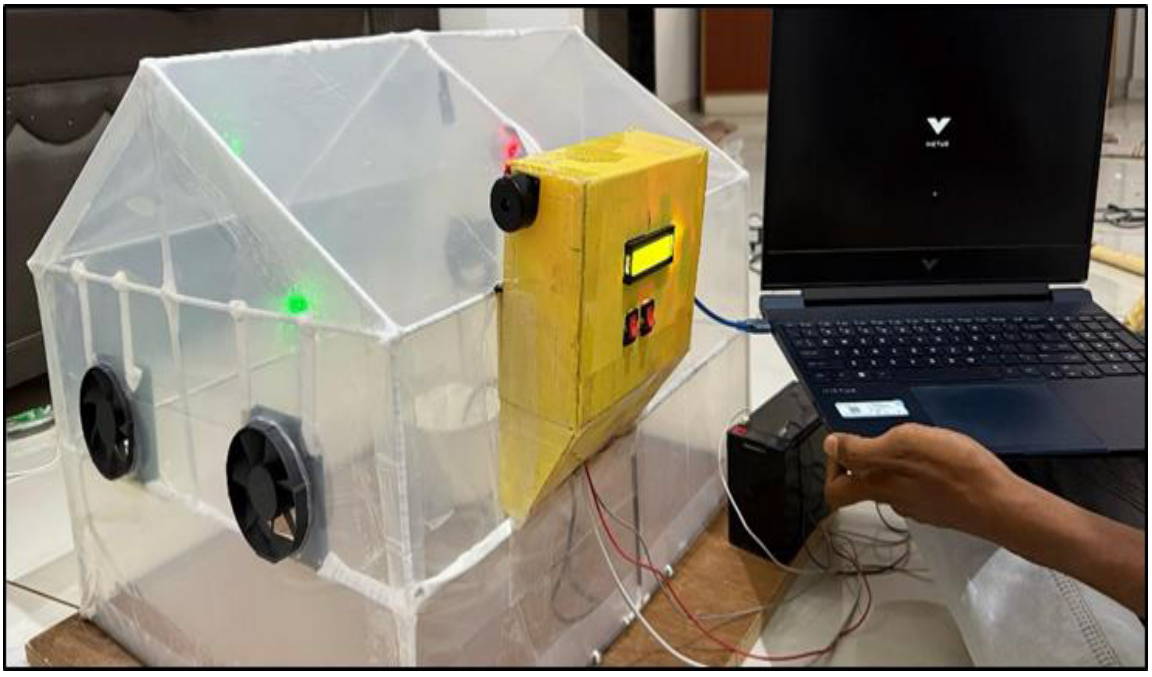


Figure 4. Fully assembled smart greenhouse prototype

Table 3. Statistical Analysis of Environmental Parameters under Automated Control

Parameter	Mean	Standard Deviation	CV (%)
Temperature (°C)	30.2	2.1	6.95
Relative Humidity (%)	58.4	4.8	8.21
Soil Moisture (%)	Optimal maintained	3.2	—

system response time was analyzed, revealing an average activation delay of 1.3 ± 0.2 seconds, indicating reliable real-time actuation.

Real-Time Monitoring and Display

The integrated 16×2 LCD operated without lag, accurately displaying live data from all active sensors, including temperature, humidity, and soil moisture. This enabled the operator to observe real-time values and confirm system responses during manual validation trials. The system proved capable of functioning independently without the need for constant human oversight.

Power Performance and Reliability

The energy supply system comprising a 12V 7.5Ah lead-acid battery recharged by a 12V solar panel was evaluated for backup and sustainability. Under full sunlight, the solar panel charged the battery sufficiently to support continuous operation for 8-10 hours even on semi-cloudy days. No functional breakdowns were observed due to power limitations during testing. The buck converter provided a stable 5V output for components such as the Arduino board, sensors, and relays.

Cost Analysis

The total cost of the prototype was approximately 5,030, covering the structure, sensors, relays, Arduino board, battery, solar panel, and wiring. This cost-effectiveness makes the system suitable for student projects, smallholder farmers, and urban growers. The affordability factor also supports future scaling or replication in multiple micro-farming units.

System Response and Limitations

The system's response time from sensor detection to actuator activation ranged from 1 to 2 seconds, indicating reliable automation. In addition to environmental stability, the control system's responsiveness was assessed by measuring the time interval between sensor detection and actuator activation. The average response time recorded for different control events is summarized in Table 4.

The low response time confirms reliable real-time automation performance. However, occasional fluctuations in soil moisture readings were noted due to loose connections on the breadboard during long-duration trials. This suggests that a soldered printed circuit board (PCB) version or a weatherproof casing would be preferable for long-term field use. Also, the DHT11 sensor has moderate accuracy (+/-2 °C, +/-5 % RH) and could be replaced with the DHT22 or SHT31 in future versions to improve precision.

Discussion in Context

The prototype validates the potential of low-cost IoT-based smart greenhouses to maintain optimal growing conditions through automation. Similar findings have been reported by Akpulonu *et al.,* 2024 and Sujin *et al.,* 2021, but their designs involve cloud-based systems and complex dashboards, making them less accessible to grassroots users. In contrast, this design emphasizes local control, offline operation, and solar-powered independence, making it ideal for rural and resource-constrained settings. The 31 ° roof angle also contributes to structural efficiency by minimizing wind drag and thermal loss. Similar IoT-based greenhouse

Table 4. Average Sensor-Actuator Response Time

Sensor	Trigger Condition	Actuator	Average Response Time (sec)
DHT11	Temp > 27 °C	Exhaust Fan	1.2
Soil Moisture	Below threshold	Pump	1.5
LDR	Low light	LED	1.1
Humidity	<50 %	Humidifier	1.4

Table 5. Comparison with Previously Reported IoT-based Greenhouse Systems

Study	Akpulonu *et al.*, 2024	Sujin *et al.*, 2021	Present Study
System Architecture	Cloud-based IoT	IoT-enabled Monitoring	Standalone Solar-powered IoT
Power Source	Grid	Grid	Solar PV
Internet Requirement	Required	Required	Not Required (Offline Operation)
Approx. Cost	High	Moderate	₹5,030
Intended Application	Commercial greenhouse	Protected cultivation	Smallholder greenhouse

models have been demonstrated by Singh *et al.*, 2019. To position the present system within the existing body of IoT-based greenhouse research, a comparative analysis was conducted across system architecture, power source, cost considerations, and applicability. The comparison with previously reported studies is presented in Table 5.

Compared with previously reported greenhouse monitoring systems, the proposed system employs a standalone solar-powered IoT architecture that enables reliable offline operation without requiring continuous internet connectivity. The system was developed at an approximate cost of ☐5,030, making it a cost-effective solution for greenhouse environmental monitoring. Its low-cost, internet-independent design makes it particularly suitable for smallholder farmers and remote agricultural locations where reliable internet access is limited. These characteristics demonstrate the potential of the proposed system as an affordable, energy-efficient, and sustainable solution for protected cultivation under resource-constrained conditions.

CONCLUSION

This study presents the successful development of a compact, solar-powered smart greenhouse prototype integrated with IoT technology for automated environmental control. The system effectively monitored and regulated temperature, humidity, soil moisture, and light intensity using low-cost sensors and actuators controlled by an Arduino Uno microcontroller. Results from real-time testing demonstrated reliable automated operation with minimal manual intervention. The standalone IoT architecture, offline operation, and low development cost (approximately ☐5,030) makes the proposed system particularly suitable for smallholder farmers and resource-constrained agricultural environments. The prototype also revealed certain limitations, including the moderate accuracy of low-cost sensors (DHT11 and YL-69) and circuit instability associated with breadboard-based wiring, which may limit long-term field deployment. Future work should focus on integrating higher-accuracy sensors, PCB implementation, and wireless data logging or mobile application support to improve system performance and usability. Overall, the developed prototype provides a practical and cost-effective foundation for smart greenhouse monitoring systems and has the potential to support sustainable protected cultivation and precision agriculture.

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Ethics Statement:

This study did not involve human participants or animals. Therefore, ethical approval was not required. The research involved only electronic components, microcontrollers, and non-living plant simulation models.

Originality and Plagiarism:

The authors confirm that this manuscript is their original work and has not been published elsewhere. All sources used have been appropriately cited, and the content has been checked for plagiarism to ensure academic integrity.

Consent for Publication:

All authors must agree to the content of the article and its publication in the journal.

Competing Interests:

The authors declare that there are no known financial or non-financial competing interests that could have appeared to influence the work reported in this paper.

Data Availability:

All data generated or analyzed during this study are included in this manuscript. The Arduino source code and additional materials are available from the corresponding author upon reasonable request.

Author Contributions:

Umangkumar B. Zalavadiya conceived the research idea, designed the study, conducted the experiments, analyzed the data, and drafted the manuscript. Umangkumar B. Zalavadiya and Divyesh Rameshbhai Vaghela jointly contributed to hardware development, programming, data interpretation, and manuscript preparation. Both authors critically reviewed the manuscript and approved the final version for publication.

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