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

**ABSTRACT**

Agricultural productivity is increasingly threatened by climate variability, resource limitations, and the need for sustainable intensification. Traditional farming systems are often labor intensive and inefficient in 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, 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, contributing to enhanced agricultural efficiency and food security.

**Keywords:** Smart 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 practices, especially in open field conditions, are often inefficient in managing essential parameters such as soil moisture, temperature, humidity, and light intensity, which directly impact plant growth and yield. Moreover, traditional methods demand constant manual monitoring and labour, 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 IoT based systems (Patil and Kale, 2016; Mohanraj *et al.*, 2016).

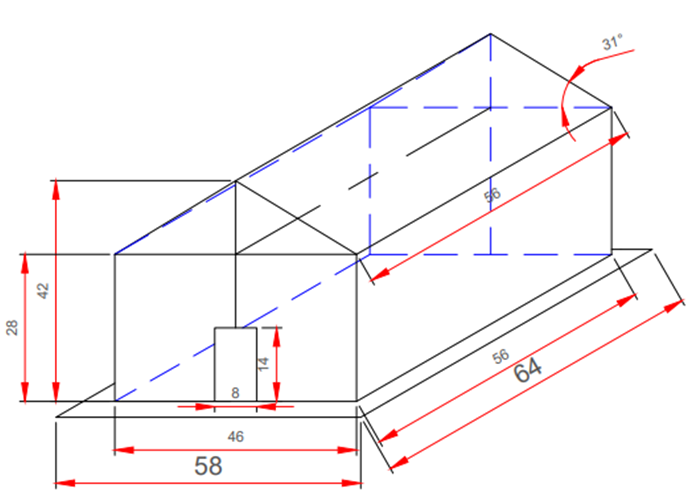
Greenhouse cultivation offers a controlled environment for year-round crop production and mitigates challenges posed by unpredictable weather. However, conventional greenhouses still require frequent human intervention and are often energy and water intensive (Thomopoulos *et al.*, 2024). With the advent of digital technologies, the integration of Internet of Things (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 *et al.*, 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 (Ahamed *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 mild steel rods of 3 mm diameter 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 (TNAU, 2023). 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.



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

### *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 following sensors were connected to the Arduino via analog and digital pins, using jumper wires and a breadboard for circuit prototyping (Mohanraj *et al.*, 2016; Ahamed *et al.*, 2020).

* **DHT11 (Temperature and Humidity Sensor)**: Measures ambient air temperature (°C) and relative humidity (%).
* **YL-69 with LM393 module (Soil Moisture Sensor)**: Detects volumetric water content in soil through analog and digital output.
* **MQ-135 Gas Sensor**: Monitors carbon dioxide (CO₂) concentration and indoor air quality.
* **LDR (Light Dependent Resistor)**: Senses ambient light intensity to trigger artificial lighting when necessary.

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

### *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. The battery was charged by a **12V solar panel**. A **DC-DC buck converter (LM2596)** stepped down 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 defined using if **conditions** that activated actuators based on real-time sensor readings. For example:

* If temperature > 27 °C → Exhaust fan ON
* If soil moisture < threshold → Water pump ON
* If light intensity LOW → Grow light ON
* If humidity < 50 % → Humidifier ON

A **16×2 LCD display (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 along with their specifications and function in **Table 1**.

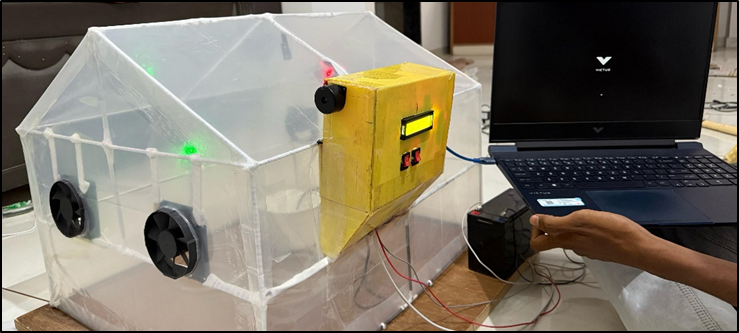
### Table 1. Components used with specifications and functions

|  |  |  |
| --- | --- | --- |
| **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 | CO₂ 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 |

**RESULTS AND DISCUSSION**

### *System Functionality and Sensor Performance*

The smart greenhouse prototype was tested under real environmental conditions over multiple cycles during the daytime 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 exhaust and intake fans when it rose above **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 dryness exceeded the pre-set threshold, ensuring timely watering. This avoided overwatering and demonstrated water-use efficiency, which is 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. The fully assembled and operational prototype is shown in **Figure 2**, demonstrating the integration of all control, sensing, and actuation components.



**Figure 2. Fully assembled smart greenhouse prototype**

### *Real Time Monitoring and Display*

The integrated **16×2 LCD display** functioned without lag, accurately presenting live data from all active sensors, including temperature, humidity, and soil moisture status. 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 stable voltage output for 5V components such as the Arduino board, sensors, and relays.

### *Cost Analysis*

The total cost of the project was approximately ₹5,030 INR, 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 between **1-2 seconds**, indicating reliable automation. However, occasional fluctuations were noted in soil moisture readings due to loose connections on the breadboard during long duration trials. This suggests that a soldered 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 **DHT22 or SHT31** in future versions for improved precision.

### *Discussion in Context*

The prototype validates the potential of **low-cost IoT-based smart greenhouses** in maintaining 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 (TNAU, 2023; Maher *et al.*, 2008). Similar IoT based greenhouse models have demonstrated by Singh *et al.* (2019). The project supports India’s push toward **smart farming**, aligning with the objectives of the National Mission on Sustainable Agriculture. With further improvements in sensor precision and system casing, such models can contribute meaningfully to year-round vegetable cultivation, training programs, and agri-tech demonstrations in academic institutes.

**CONCLUSION**

This study presents the successful development of a compact, 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 automation, energy efficiency, and minimal need for manual intervention, highlighting its relevance to smallholder farming, urban agriculture, and educational applications. The findings underscore the potential of accessible digital technologies in enhancing precision agriculture, resource conservation, and crop productivity under protected cultivation. However, the prototype also revealed certain limitations, such as moderate sensor accuracy (e.g., DHT11, YL-69) and circuit instability due to breadboard wiring, which may restrict long-term deployment in field conditions. Future iterations should explore the use of more accurate sensors, soldered PCB circuitry, and wireless data logging or mobile app integration to enhance performance and usability. Despite these limitations, the prototype stands as a scalable, energy-efficient solution aligned with sustainable farming goals, and it lays a promising foundation for future innovations in smart, climate-resilient 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 have reviewed the manuscript and give their full consent for its publication in the *Madras Agricultural 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 analysed 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**

All authors contributed equally to the conception, design, execution, and writing of this research work. They collaborated on hardware development, programming, data analysis, and manuscript preparation. All authors reviewed and approved the final version of the manuscript.

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