

Development of Automated Miniature Greenhouse for Real-Time Monitoring of Environmental Parameters

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ABSTRACT

Greenhouse cultivation requires continuous monitoring of environmental and soil conditions to support plant growth. Manual monitoring can be time-consuming and may not ensure consistent control. This study developed and evaluated an automated miniature greenhouse system that monitors environmental parameters and activates devices based on preset thresholds. The system used an Arduino Uno microcontroller integrated with soil moisture, soil temperature, DHT11, LDR, and MQ gas sensors. Relay modules controlled a ventilation fan, water pump, and artificial light. Solar energy was used to support the microcontroller power supply. System evaluation included calibration testing, three-trial sensor accuracy testing, and seven-day operational monitoring.

Calibration results confirmed correct wiring and proper communication between components. Accuracy testing showed consistent readings across three trials: temperature at 26°C, humidity between 54% and 55%, soil moisture averaging 28.82%, carbon dioxide at 8130 ppm, methane at 0 ppm, and light intensity averaging 31 lux. Actuators operated according to programmed conditions. During the seven-day monitoring period, temperature ranged from 25–27°C, humidity from 53–61%, and soil moisture changes triggered water pump activation on Day 7. Increased light intensity on Day 3 activated the artificial lighting system. A soil temperature sensor error was observed and requires correction. The results indicate that the system can monitor environmental conditions and perform automated control within the set parameters.

Keywords: greenhouse automation, Arduino, environmental monitoring, sensor testing, automated control

INTRODUCTION

Greenhouses play a vital role in modern agriculture by creating controlled environments that enhance plant growth, improve yields, and extend planting seasons (Allali et al., 2025). However, achieving and maintaining optimal growing conditions requires continuous monitoring of environmental and soil parameters such as temperature, humidity, soil moisture, and pH (Kumar et al., 2024). Traditional methods of monitoring are labor-intensive, time-consuming, and often fail to provide real-time accuracy needed for efficient management (Essamlali et al., 2024).

Automation technologies have recently provided smart solutions in agriculture by integrating sensors, microcontrollers, and programmed actuators to support real-time decision-making and reduce manual workload (Rothe et al., 2025). When powered by renewable energy, such as solar energy, automated systems become sustainable and reliable, particularly for off-grid agricultural settings (Garraín & Lechón, 2023).

This study focuses on the development of an automated miniature greenhouse designed for real-time monitoring and control of environmental and soil parameters. By using sensors, a microcontroller, relays, and an LCD display, the system is designed to automatically regulate actuators such as fans, water pumps, and artificial lights when parameter thresholds deviate from optimal ranges. This reduces manual effort, enhances monitoring accuracy, and promotes sustainable greenhouse practices.

Statement of the Problem

Efficient greenhouse management requires real-time monitoring and control of environmental and soil parameters to ensure optimal plant growth (Asane et al., 2025). Conventional approaches are limited because they rely on manual observation, are labor-intensive, and often lack the accuracy needed for immediate response. Furthermore, reliance on traditional power sources increases operational costs and limits application in rural or off-grid settings (Salac et al., 2024).

Although many studies focus on IoT-enabled smart greenhouses, there is a research gap in developing a self-sustaining, automated greenhouse system that operates without dependence on wireless communication or external monitoring platforms (Muthukumar & Karthick, 2025). This study addresses this gap by designing and testing a automated miniature greenhouse capable of real-time monitoring and automatic actuation of environmental controls.

Research Objectives

The general objective of this study is to develop a solar-powered automated miniature greenhouse for real-time monitoring and control of environmental and soil parameters. Specifically, it aims to:

1. Design miniature greenhouse system integrated with automation technology;
2. Develop a sensor-based monitoring system for key parameters such as temperature, humidity, soil moisture, methane, and CO₂;
3. Display real-time soil and environmental parameters on a liquid crystal display module;
4. Implement automatic actuation (fan, water pump, and artificial light) based on pre-set threshold values;
5. Test the system's performance using calibration, sensor accuracy and daily monitoring tests.

Hypothesis

This study hypothesizes that a solar-powered automated miniature greenhouse will provide reliable and sustainable real-time monitoring and control of environmental and soil parameters, thereby improving greenhouse management and supporting sustainable agricultural practices.

Literature Overview of Sensors and Needs for Environmental Monitoring

Environmental monitoring requires sensors that can detect contaminants across categories such as metals, radioisotopes, volatile organic compounds (VOCs), and biological agents. Ho et al. (2005), in the article Overview of Sensors and Needs for Environmental Monitoring, provided a comprehensive review of emerging sensor technologies suitable for these applications. The study emphasized the potential of laser induced breakdown spectroscopy (LIBS) for detecting trace metals and ion mobility spectrometry (IMS) for semi volatile compounds, both of which demonstrated capabilities at or below regulatory concentration levels. Additional technologies such as cadmium zinc telluride (CZT) sensors for radioisotopes, MicroChemLab for VOC detection, and Bio Saw for biological contaminants were identified as promising but requiring further research and optimization. Key performance factors including sensitivity, selectivity, stability, and cost were highlighted as critical challenges for successful field deployment. The review concluded that LIBS and IMS hold the most immediate promise for environmental applications, particularly in monitoring drinking water and ambient air quality (Ho et al., 2005). In the context of the present study on the development of a solar powered IoT based miniature greenhouse for real time monitoring of environmental and soil parameters, these insights underscore the importance of selecting sensor technologies that balance sensitivity and reliability while remaining adaptable to fluctuating environmental conditions.

Monitoring soil quality of different land use systems

Soil quality is highly influenced by land use and land cover changes, which directly affect both physical and chemical soil indicators. Yeneneh et al. (2024), in their study Monitoring soil quality of different land use systems: a case study in Suha watershed, northwestern highlands of Ethiopia, assessed the impacts of land conversion on

soil conditions and agricultural productivity. The findings revealed that the transition from forest land to agricultural land resulted in significant deterioration of soil quality, with soil organic carbon (SOC) depletion and nitrogen deficiency being the major contributors. Soil quality indicators were found to be below threshold values, particularly in cultivated fields, highlighting poor land management and the degradation of soil ecosystem services. The soil quality degradation index further confirmed negative values across most agricultural sites, while aggregated soil quality index values remained below the optimum range. The study emphasized that poor agricultural practices are a leading cause of reduced soil fertility and productivity. To address these challenges, the authors recommended the adoption of integrated soil fertility management (ISFM) strategies and soil conservation technologies tailored to site specific conditions (Yeneneh et al., 2024). In relation to the present study on the development of a solar powered IoT based miniature greenhouse, these insights underscore the importance of monitoring soil parameters in real time to detect early signs of deterioration and support precision management practices that sustain soil health and agricultural productivity.

Automated Prototype Arduino-Based Mini-Greenhouse for Agricultural Sustainability

Emnacin et al. (2023), in their study Automated Prototype Arduino-Based Mini-Greenhouse for Agricultural Sustainability, explored the feasibility of employing automation to improve greenhouse farming efficiency. The results demonstrated that integrating sensors and controlled components into the prototype significantly enhanced plant growth. Soil moisture sensors played a central role in facilitating water conservation and efficient irrigation, while the regulation of humidity and temperature created optimal conditions for cultivation. Furthermore, the inclusion of LED lighting provided a cost-effective strategy for managing light cycles, thereby supporting plant development. The study emphasized the versatility and efficiency of the Arduino UNO microcontroller as a foundation for building adaptable and sustainable agricultural systems. These findings illustrate how Arduino-based automation can serve as a transformative and enduring solution to modern agricultural challenges (Emnacin et al., 2023). In relation to the development of a solar powered IoT based miniature greenhouse, this work highlights the importance of microcontroller-driven automation and real-time sensing as critical tools to optimize environmental control, conserve resources, and strengthen sustainability in protected agriculture.

Remote Sensing Applications in Agriculture

Verma et al. (2024), in their book chapter Remote Sensing Applications in Agriculture, emphasized the transformative role of remote sensing technologies in advancing precision agriculture. The study highlighted how these technologies provide vital insights across all stages of crop production, from field preparation and planting to monitoring and harvesting. Remote sensing enables early warning systems that help farmers respond proactively to environmental stresses and crop health issues, thereby optimizing yields. Advances in sensor technology, data analytics, and spectral resolution have expanded the possibilities of remote sensing, particularly in evaluating grain quality and monitoring growth stages. Additionally, the integration of remote sensing with climate models has been identified as a promising approach for forecasting crop growth scenarios, supporting breeding programs, and ensuring sustainable agricultural practices.

Despite its potential, the study acknowledged challenges in terms of cost, effectiveness, and applicability across different farming systems. Nonetheless, remote sensing stands out as a non-destructive, precise, and scalable method for agricultural monitoring and management. In the context of the development of a solar powered IoT based miniature greenhouse, the findings underscore the importance of integrating remote sensing with IoT systems to enable real-time monitoring, predictive modeling, and sustainable resource management in protected agriculture.

METHODOLOGY

Research Design

This study utilizes a developmental research design as it focuses on the design, construction, and evaluation of an automated miniature greenhouse for real-time monitoring and control of environmental and soil parameters. The research follows a systematic process beginning with the planning and design of the system, followed by

prototype development and integration of sensors, microcontroller, relay modules, LCD display, and solar power. The completed prototype is then subjected to testing to evaluate its performance in terms of accuracy, reliability, and sustainability. The results are analyzed using descriptive statistics to determine the system's effectiveness and to identify areas for refinement.

General Block Diagram

The general architecture of the automated miniature greenhouse is depicted in Figure 1, illustrating a closed loop control system integrated within a sustainable energy framework. In this configuration, a solar panel harvests energy for storage in a battery to power the Arduino Uno microcontroller, while auxiliary loads are managed via an external power supply to maintain system stability and signal integrity. As the central processing unit, the Arduino Uno interfaces with a multiparameter sensor array including soil moisture, ambient temperature, humidity, light intensity, and gas sensors to monitor the internal environment against preprogrammed critical thresholds. Upon reaching these levels, the microcontroller transmits signals to a four channel relay module, which modulates the operation of the ventilation fan, water pump, and artificial lighting in a normally closed (NC) connection. This integrated logic ensures precise environmental regulation, with all measured parameters concurrently output to a Liquid Crystal Display (LCD) for real time monitoring.

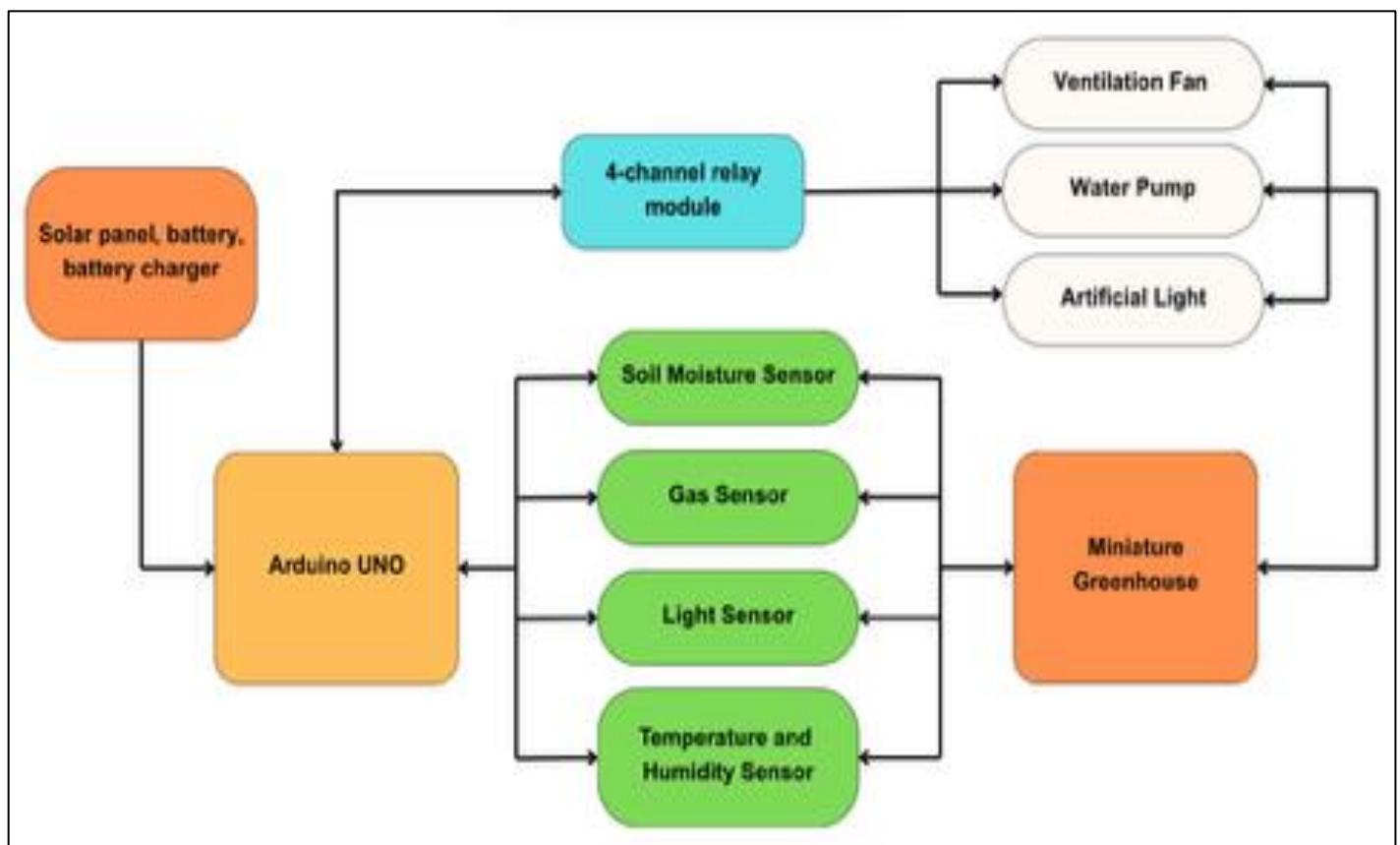


Figure 1 General Block Diagram

The operational logic of the miniature greenhouse system is illustrated in the flowchart in Figure 2 which details the sequential execution of monitoring and control tasks. The cycle initiates with the generation and distribution of electrical power from the solar panel to the central processing unit. Following system initialization the Arduino Uno performs a data acquisition phase where it reads input from the integrated sensors for soil moisture ambient temperature humidity light intensity and gas concentrations.

These digital and analog signals are processed and compared against preprogrammed threshold conditions stored in the system memory. The control logic follows a conditional execution sequence: when the soil moisture level falls below the critical set point the microcontroller sends a signal to the relay module to activate the water pump for irrigation. Similarly the detection of high ambient temperature or humidity levels triggers the ventilation fan

to facilitate heat dissipation and airflow. In conditions of low luminous intensity the artificial lighting system is switched on to maintain optimal photosynthetic conditions. After the evaluation of all parameters the system updates the LCD with real time measurements to provide visual feedback for the user. This process operates as a continuous closed loop ensuring that the internal greenhouse environment remains within the desired parameters for plant development.

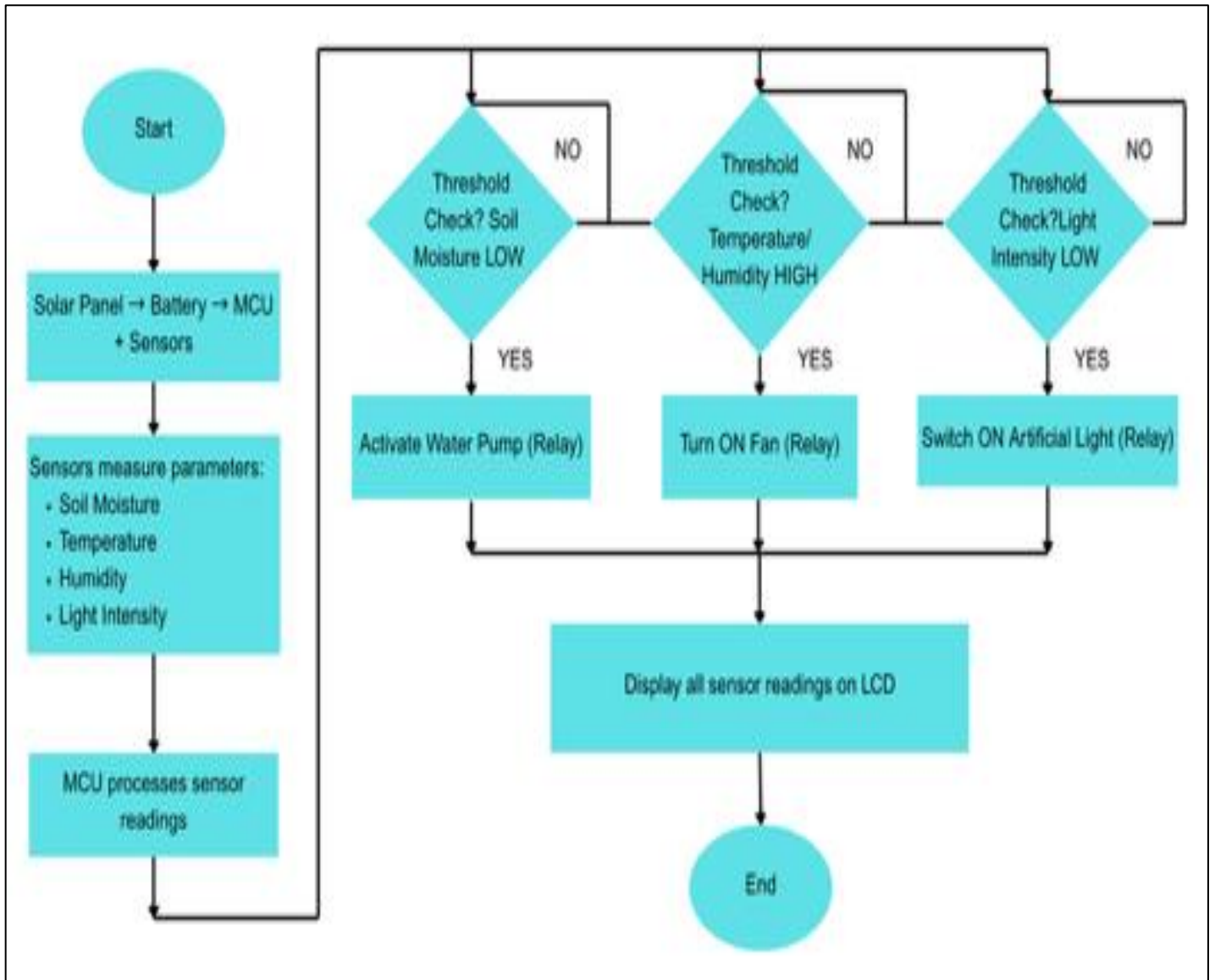


Figure 2 Flow Chart

Hardware Design

The methodology for the physical construction and integration of the greenhouse follows a systematic hardware deployment plan to ensure environmental stability and modular maintenance. The structural phase involves the fabrication of a furnished wooden framework, which is subsequently encapsulated in vinyl plastic to provide a weather resistant barrier while mitigating the impact of excessive ultraviolet exposure on plant health.

Following the structural assembly, a strategic spatial distribution plan is executed to optimize the performance of the automated subsystems. The power harvesting and luminosity regulation components, including the solar panel, light sensor, and artificial lighting, are situated at the uppermost section of the frame for maximum exposure. The atmospheric monitoring array is positioned on the left side of the structure to track temperature, humidity, and gas concentrations, while the irrigation unit is installed at the lower right quadrant to facilitate water delivery from the reservoir to the soil tub. To streamline system organization and improve accessibility for future maintenance, the plan includes the installation of a centralized control box on the exterior side of the

greenhouse. This enclosure houses the Arduino Uno, the four channel relay module, and the LCD interface for real time data visualization, while a ventilation fan is integrated near the control unit to ensure consistent airflow and heat dissipation throughout the internal environment.

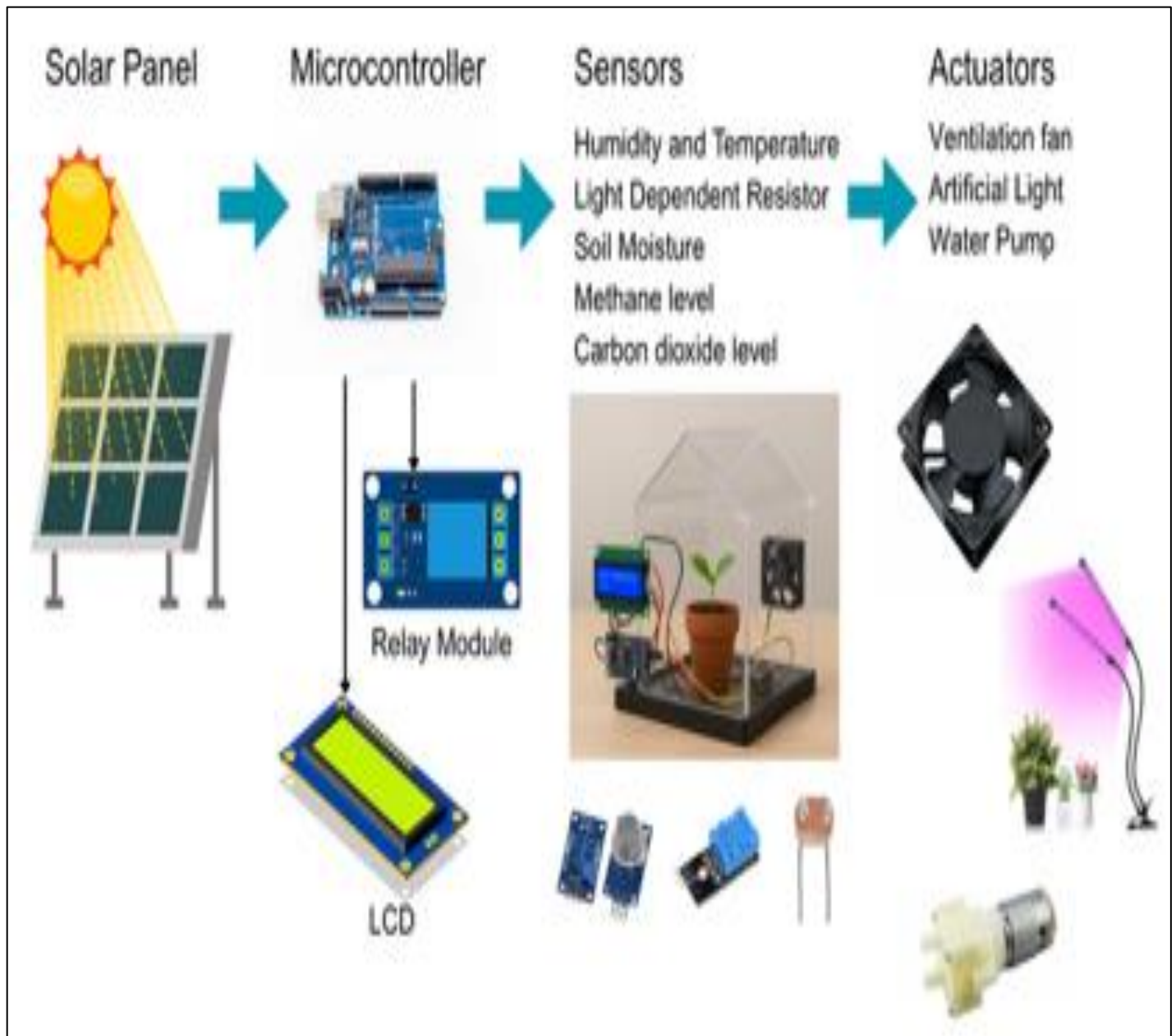


Figure 3 Workflow Diagram

Schematic Diagram

Figure 4 shows the schematic diagram of the developed automated monitoring and control system. In this design, the researchers used an Arduino Uno as the main microcontroller to acquire sensor data, process the collected information, and control the output devices.

The researchers integrated multiple sensors, including soil moisture, soil temperature, DHT11 (temperature and humidity), LDR, and MQ2 and MQ9 gas sensors, to monitor environmental parameters. These sensors transmit signals to the Arduino for real-time analysis. An I2C LCD was incorporated to display the measured values and system status.

For the control mechanism, the researchers utilized a single relay module and a dual relay module to operate the ventilation fan, water pump, and UV light. A 12V power supply regulated to 5V using a buck converter provided

stable voltage to the system, while a solar panel and 9V battery were connected through a power bus for supplemental energy management.

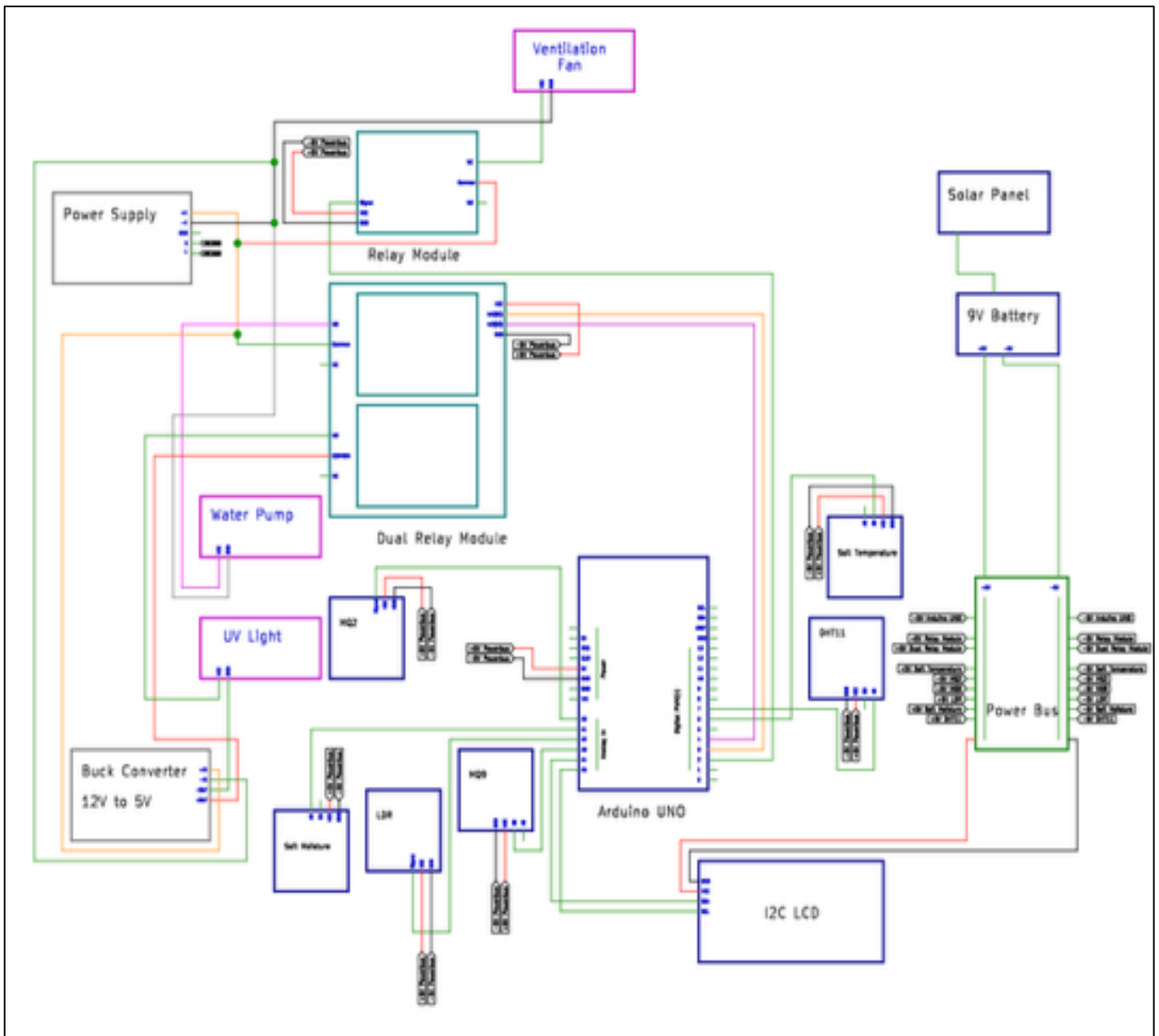


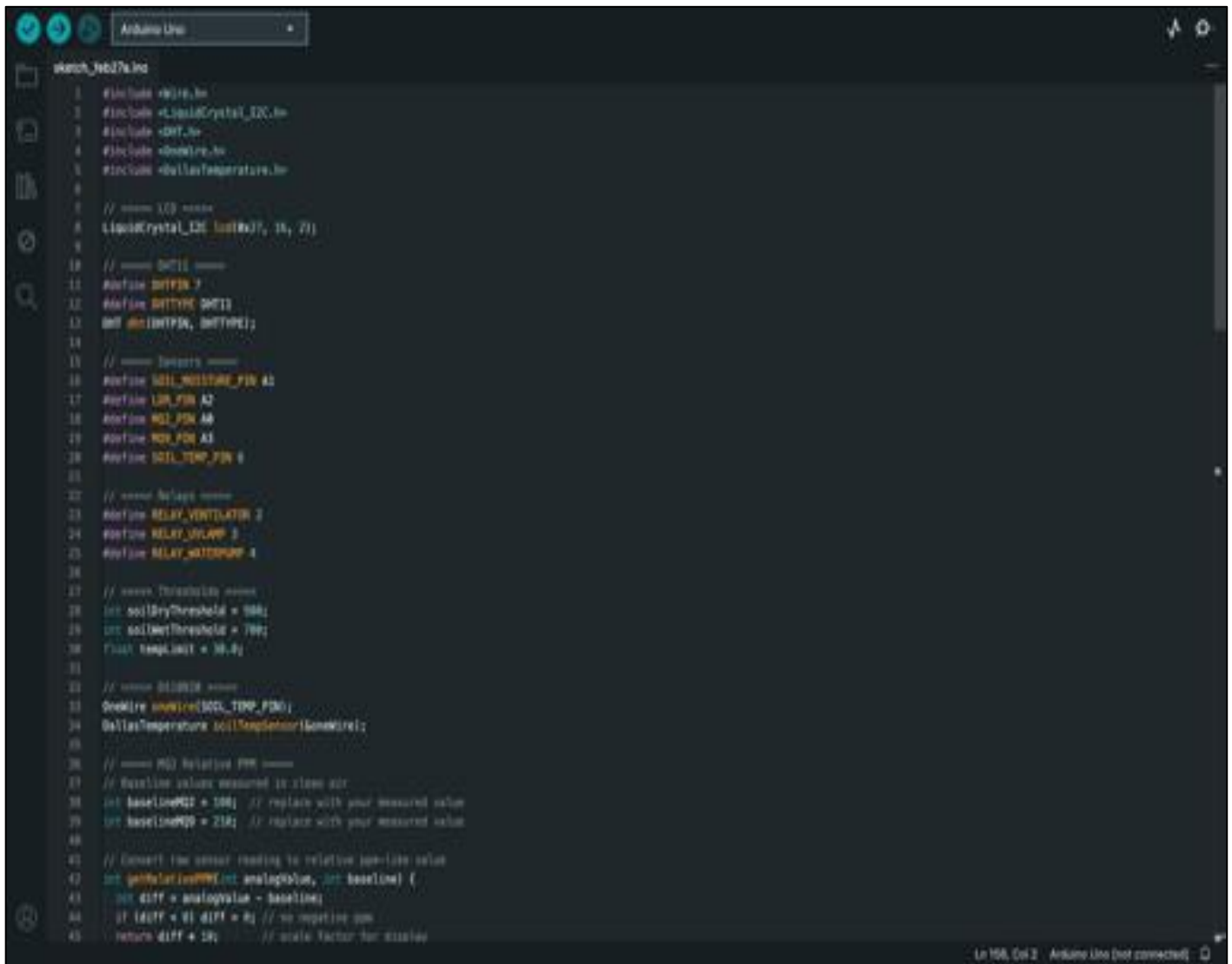
Figure 4 Schematic Diagram

Software Implementation

The system was developed using the Arduino environment and implemented on an Arduino Uno to integrate environmental sensors, an LCD display, and relay-controlled actuators into an automated monitoring platform. The copy of the source code shown in Figure 5 presents the inclusion of essential libraries such as Wire.h, LiquidCrystal_I2C.h, DHT.h, OneWire.h, and DallasTemperature.h, which enable I2C communication, temperature–humidity sensing, and digital soil temperature acquisition. The 16×2 I2C LCD (address 0x27) is initialized in the program to display real-time sensor readings and system status.

As reflected in the figure, pin assignments are defined using preprocessor directives to ensure clarity and modular implementation. The DHT11 sensor is connected to a designated digital pin, while the soil moisture sensor, LDR, NPK sensor, and MQ gas sensor are assigned to specific analog input pins. The soil temperature sensor communicates through the OneWire protocol. Relay outputs are configured to control the ventilation fan, lighting system, and water pump based on predefined soil moisture thresholds and calibrated gas baseline values. This

structured organization of the code enables coordinated sensing, data processing, and automated environmental control within the developed smart monitoring system.



```

1 // sketch_16037a.ino
2 #include <Wire.h>
3 #include <LiquidCrystal_I2C.h>
4 #include <DHT.h>
5 #include <OneWire.h>
6 #include <DallasTemperature.h>
7
8 // ===== LCD =====
9 LiquidCrystal_I2C lcd(0x27, 16, 2);
10
11 // ===== DHT11 =====
12 #define DHTPIN 7
13 #define DHTTYPE DHT11
14 DHT dht(DHTPIN, DHTTYPE);
15
16 // ===== Sensors =====
17 #define SOIL_MOISTURE_PIN A1
18 #define LDR_PIN A2
19 #define MQ1_PIN A0
20 #define MQ2_PIN A3
21 #define SOIL_TEMP_PIN 0
22
23 // ===== Relays =====
24 #define RELAY_VENTILATOR 2
25 #define RELAY_SHLAMP 3
26 #define RELAY_WATERPUMP 4
27
28 // ===== Thresholds =====
29 int soilDryThreshold = 500;
30 int soilWetThreshold = 700;
31 float tempLimit = 30.0;
32
33 // ===== DHT11 =====
34 OneWire oneWire(SOIL_TEMP_PIN);
35 DallasTemperature tempSensor(oneWire);
36
37 // ===== MQ1 Relative PPM =====
38 // Baseline values measured in clean air
39 int baselineMQ1 = 100; // replace with your measured value
40 int baselineMQ2 = 210; // replace with your measured value
41
42 // Convert the sensor reading to relative ppm-like value
43 int getRelativePPM(int analogVal, int baseline) {
44   int diff = analogVal - baseline;
45   if (diff < 0) diff = 0; // no negative ppm
46   return diff + 10; // scale factor for display
47

```

Figure 5 Program Initialization

Testing

The testing of the developed greenhouse monitoring and control system was conducted in three major stages to evaluate functionality, accuracy, reliability, and operational stability.

Stage 1: Arduino and Sensor Calibration Testing (Kulmány et al., 2022)

The first stage involved calibrating the Arduino and integrated sensors by uploading diagnostic and simulation codes. This process verified the functionality and communication between the microcontroller and each sensor. Three simulation trials were conducted to assess consistency of readings and response time under controlled conditions. The goal of this stage was to ensure proper wiring, correct sensor mapping, stable voltage supply, and reliable data acquisition before actual deployment. Any discrepancies observed during simulation were corrected through code refinement and hardware adjustments.

Stage 2: Sensory Accuracy and Actuator Response Testing (Tjiptoyuda, 2023)

The second stage focused on evaluating sensor accuracy in the actual greenhouse environment. The sensors were deployed and tested for three trials while monitoring critical environmental parameters such as temperature, humidity, soil moisture, light intensity, and gas levels. Actual environmental conditions were observed and

compared with sensor readings to assess accuracy and consistency. In addition, the response of actuators, including the ventilation fan, artificial light, and water pump was monitored to determine whether they were triggered appropriately based on the programmed threshold values. The primary objective of this stage was to validate the precision of measurements and confirm that the automated control mechanism responded correctly and efficiently to environmental changes.

Stage 3: Seven-Day Operational Monitoring Test (Azoulay-Kochavi et al., 2025)

The final stage involved continuous system operation inside the greenhouse for seven consecutive days. Three trials were conducted per day, and all sensor readings were recorded using actual measured values. The activation of actuators was also monitored to determine system responsiveness under real daily environmental variations. Daily averages were computed to analyze trends, stability, and performance consistency over time. This stage aimed to evaluate the long-term reliability, durability, and overall effectiveness of the developed system in maintaining optimal greenhouse conditions.

Assembly

The assembly of the developed greenhouse system began with the selection of appropriate materials to ensure durability and functionality. The miniature greenhouse structure was constructed using precisely cut wooden panels that were joined and assembled to form a stable frame. The structure was then covered with polyethylene (PE) film to simulate a real greenhouse environment while allowing proper light penetration and internal climate retention.

A separate control box was assembled to house the electronic components. The Arduino was securely mounted at the center, while the relays, LCD, and other modules were properly arranged inside. Wiring connections were carefully measured, organized, and insulated to ensure safety, minimize signal interference, and maintain system reliability.

The solar panel was installed at the upper portion of the greenhouse for maximum light exposure, and the mini power storage unit was positioned inside near the control box for efficient power distribution. The LDR and gas sensors were mounted at the upper section to ensure proper environmental exposure. At the center, a soil container was placed where the soil temperature and moisture sensors were embedded for accurate readings. A water pump was installed near the tub and connected through a hose system for automated irrigation. An artificial light was also mounted at the upper section to provide supplemental illumination when required.



Figure 6 Prototype assembly

RESULTS

This chapter presents the data gathered and the outcomes of the developmental process for the Automated Miniature Greenhouse for Real-Time Monitoring of Environmental Parameters. It details the physical and functional characteristics of the developed prototype, evaluating its performance based on real-time environmental monitoring and automated response accuracy.

Design

Figure 7 presents the actual picture of the developed prototype, showcasing a fully integrated solar-powered smart greenhouse system designed for autonomous environmental management. The unit is constructed with a white-framed enclosure and transparent paneling to ensure optimal light penetration for plant growth while housing the internal electronics. A solar panel is strategically mounted on the sloped roof to provide a power source. Central to the design is the external control hub, which features a 16x2 I2C LCD interface providing real-time telemetry for critical parameters, including ambient temperature, relative humidity and soil. The internal chamber contains a dedicated soil tray and a water reservoir linked by a submersible pump system, with red LED status indicators providing visual confirmation of sensor activation. This setup allows the system to automatically trigger irrigation and ventilation based on real-time data, ensuring a stabilized microclimate for the specimen.

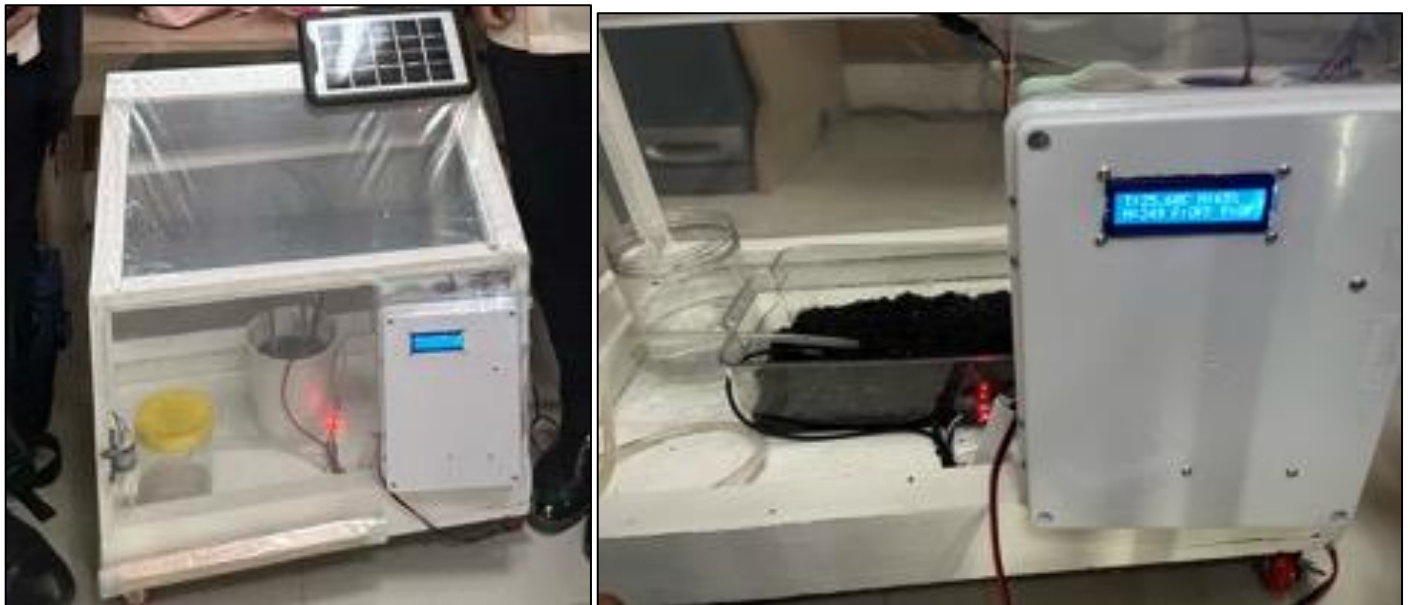


Figure 7 Developed Prototype

Test Results

The evaluation of the developed prototype was conducted in three sequential phases to ensure functional reliability: Stage 1 focuses on Arduino and Sensor Calibration Results to establish baseline precision; Stage 2 analyzes Sensor Accuracy Results against standard references; and Stage 3 documents the Seven-Day Operational Monitoring Results to verify long-term system stability and automation.

Stage 1: Arduino and Sensor Calibration Results

The initial calibration stage verified the proper functioning of the Arduino microcontroller and integrated sensors. Diagnostic and simulation codes were uploaded, and three controlled trials were conducted to evaluate signal stability and response. The sensors transmitted stable and repeatable readings without noticeable fluctuation or delay. Minor code refinements were implemented to optimize data acquisition, the results confirmed correct wiring configuration, stable voltage supply, and dependable communication between the microcontroller and all connected components prior to greenhouse deployment.

Stage 2: Sensor Accuracy Results

Sensor accuracy testing was conducted through three consecutive trials under actual greenhouse conditions. The results demonstrated readings across all measured parameters. Temperature remained constant at 26°C in all trials, indicating repeatability and zero variation. Humidity values ranged narrowly between 54% and 55%, showing minimal deviation. Soil moisture readings averaged 28.82% in the calibration scale, reflecting stable sensor performance. Carbon dioxide concentration consistently measured 8130 ppm, while methane remained at 0 ppm throughout the trials. Light intensity readings averaged 31 lux with negligible variation. The uniformity of these results confirms the stability of the sensing components. Figure 1 shows the graphical representation of the sensor accuracy test results, illustrating the consistency of readings across the three trials.

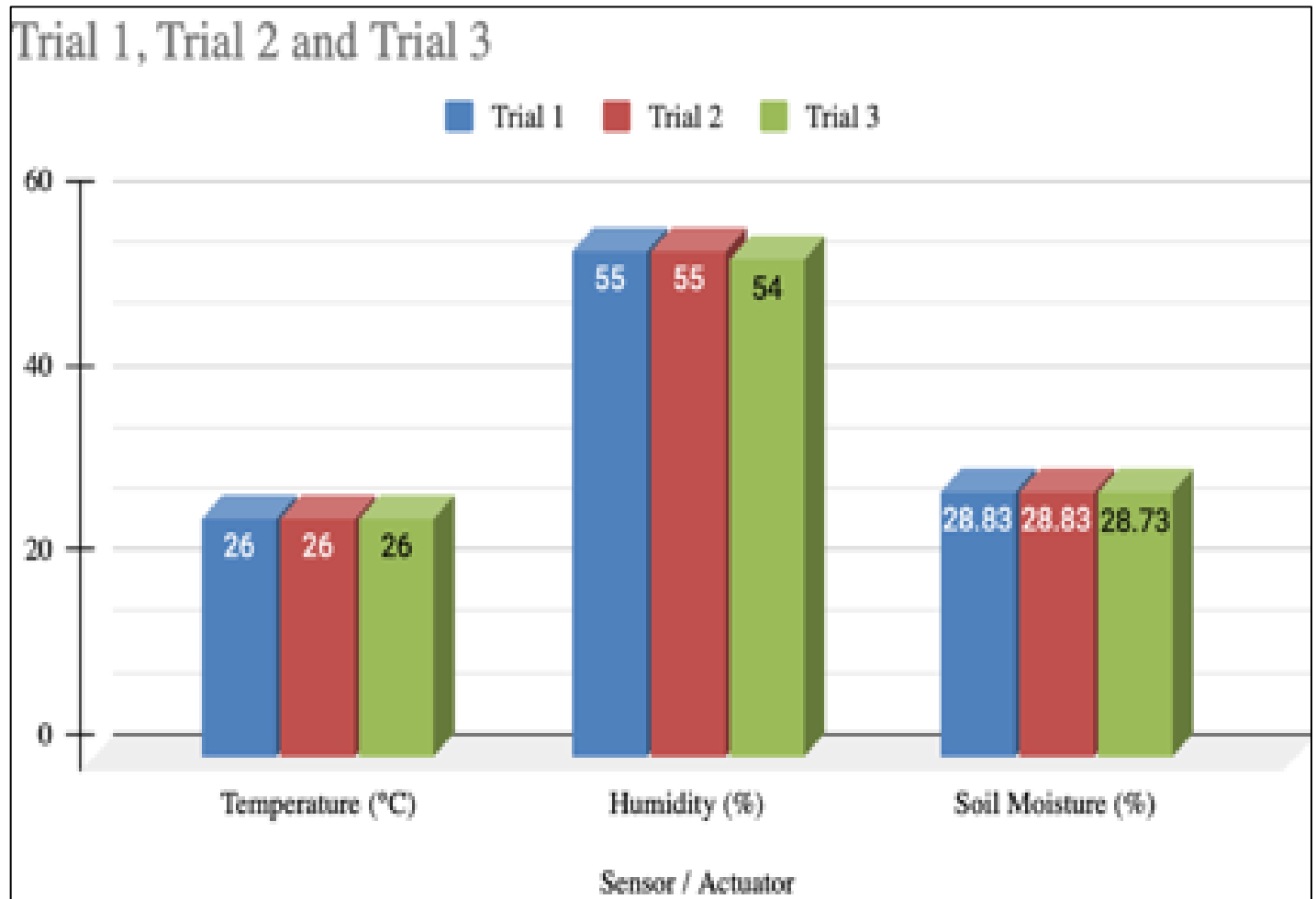


Figure 8 Sensor Accuracy Test Results

Actuator validation confirmed that the automated control mechanism responded correctly according to programmed threshold values. Since temperature did not reach the 30°C threshold, the ventilation fan remained inactive. Soil moisture readings did not meet the dryness threshold, and therefore the water pump was not triggered. Light intensity levels also remained within the programmed range, preventing artificial light activation. Manual testing verified that all actuators were fully functional and responsive when triggered.

Stage 3: Seven-Day Operational Monitoring Results

During the seven-day continuous monitoring period (Figure 9), the system demonstrated stable environmental sensing and reliable automated control. Temperature ranged from 25°C to 27°C, remaining below the activation threshold for the ventilation fan. Humidity varied between 53% and 61%, reflecting normal environmental fluctuations. Soil moisture values showed gradual changes, with a significant variation on Day 7 (Figure 10) that resulted in water pump activation. Light intensity displayed a notable increase on Day 3, which triggered the artificial lighting system based on the programmed condition.

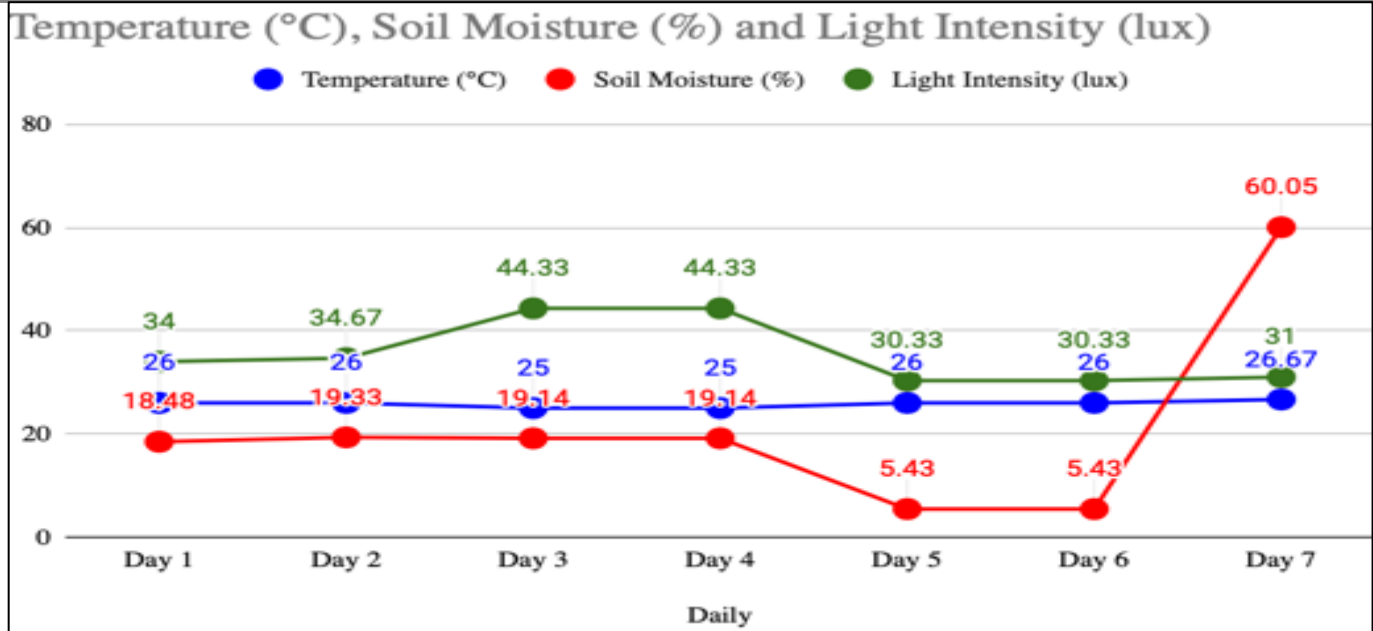


Figure 9 Temperature, Moisture and Light Intensity Test Results



Figure 10 Sample readings on the seventh day

Carbon dioxide concentration remained constant at 8130 ppm across all monitoring days, while methane levels showed a noticeable spike on Day 4 before returning to baseline values. A separate figure is included to illustrate the graphical trends of carbon dioxide (ppm) and methane (ppm), clearly presenting gas concentration behavior during the seven-day operation. The soil temperature sensor consistently displayed an invalid reading of -127°C, indicating a probable sensor malfunction or wiring error that requires corrective action. Despite this anomaly, the overall system demonstrated stable performance, accurate sensing capability, and appropriate actuator responsiveness during extended greenhouse operation.

CONCLUSION

This study successfully demonstrated the development of an automated miniature greenhouse utilizing a decentralized sensor based architecture and microcontroller logic for autonomous environmental regulation. The integrated system achieved real time monitoring of critical edaphic and atmospheric variables including soil moisture, temperature, humidity, gas concentrations, and luminous intensity. Empirical testing validated the reliability of the control logic which consistently triggered the ventilation, irrigation, and artificial lighting subsystems as parameters deviated from preprogrammed thresholds.

In comparison to existing automated greenhouse technologies reported in recent literature, this system offers a highly resource efficient alternative by integrating solar energy harvesting with a low cost Arduino framework. While industrial scale IoT solutions often require complex cloud infrastructure and high capital investment, this design prioritizes localized processing and power autonomy, making it particularly viable for small scale urban farming and decentralized agricultural research. The findings support the feasibility of scalable automation to improve monitoring efficiency while significantly reducing manual labor requirements. Future research will focus on enhancing system fault detection mechanisms and improving the long term calibration stability of the soil temperature and gas sensors to ensure higher data fidelity across diverse planting cycles.

RECOMMENDATION

Based on the experimental validation of the automated miniature greenhouse, several pathways for future development and practical implementation are proposed to enhance system reliability and impact. Technical improvements should focus on optimizing sensor data fidelity by integrating higher precision components and expanding the monitoring suite to include edaphic variables such as soil pH and nutrient levels for a more comprehensive nutritional analysis. While the current solar energy harvesting unit successfully supports the microcontroller, future iterations should scale the photovoltaic array and battery capacity to provide a completely autonomous power supply for all system components, including high current actuators. To further validate the robustness of the control logic, longitudinal studies across diverse soil types and varied plant species are recommended, particularly through real world deployment in fluctuating outdoor climates.

Beyond technical refinement, this research offers significant practical relevance across multiple sectors. In small scale farming and urban agriculture, the low cost automation framework provides a resource efficient solution for maintaining optimal yields with minimal manual intervention. Research stations can utilize the modular design to isolate and control specific environmental variables for localized botanical studies and precision agriculture experiments. Furthermore, the system serves as an essential educational platform for engineering and agricultural students, offering a tangible application for learning about IoT integration, sensor calibration, and sustainable energy systems. By addressing these recommendations, the system can transition from a functional prototype to a scalable tool for modern controlled environment agriculture.

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