

Smart Greenhouse Management: Harnessing Artificial Intelligence for Sustainable Farming

Dilbar Hussain

Iqra University

Fahiza Fauz

National University of Modern Languages

Turkia Almoustafa

`turkia.almoustafa@manchester.ac.uk`

University of Manchester

Muhammad Abbas

Sukkur IBA University

Zohran Rasheed

Sukkur IBA University

Article

Keywords: Solar-powered sprayer, Agricultural automation, Precision farming, Pesticide application, Sustainable agriculture, Remote monitoring

Posted Date: September 9th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7557629/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Greenhouse farming plays a vital role in enhancing agricultural productivity, yet it often suffers from inefficient resource management and delayed disease detection. This paper presents a novel solar-powered Smart Greenhouse Management System (SGHMS) that integrates IoT-based environmental monitoring, machine learning for real-time disease detection, and a Raspberry Pi-controlled autonomous sprayer into a unified platform. Unlike existing systems, our approach combines a CNN-based plant health classifier deployed locally on Raspberry Pi with an energy-efficient solar power source to ensure reliable off-grid operation. A user-friendly web and mobile application enables real-time monitoring, alert generation, and remote control of environmental parameters and spraying actions. The system was deployed in a real greenhouse for 30 days and demonstrated a 92% disease detection accuracy while significantly reducing water and energy consumption. This integrated solution offers a scalable and cost-effective approach to sustainable precision agriculture, particularly in resource-constrained regions.

1. INTRODUCTION

Agriculture is a vital sector that plays a crucial role in global food production and economic stability. However, the increasing reliance on chemical pesticides for crop protection poses significant health risks to farmers and the environment. Prolonged exposure to these chemicals can lead to severe health issues, including respiratory problems, skin irritations, and long-term chronic conditions (Tudi et al., 2021). The increasing demand for sustainable agricultural practices has highlighted the need for more efficient and intelligent greenhouse management systems. This research aims to develop a state-of-the-art greenhouse management system that integrates renewable energy sources and intelligent monitoring to optimize resource usage, improve plant growth, and enable early disease detection. To ensure energy efficiency and sustainability, the system will incorporate solar panel technology, providing a renewable power source for uninterrupted operation. Additionally, machine learning algorithms will be developed to enable early disease detection, empowering greenhouse operators with the ability to act swiftly and prevent crop damage. A user-friendly web application will be designed, allowing operators to remotely monitor and control greenhouse conditions, receive real-time alerts, and take necessary actions to ensure optimal plant health.

In contrast to previous systems, this work introduces a holistic, energy-autonomous smart greenhouse platform that integrates real-time sensing, edge-based disease classification using convolutional neural networks, and automated pesticide spraying in a solar-powered architecture. This system uniquely combines remote accessibility, localized machine learning, and IoT-actuated control into a single deployable prototype tested in real-world conditions.

The research will be tested and evaluated in real-world greenhouse environments to assess its accuracy, reliability, energy efficiency, and overall usability. The integration of automation, real-time monitoring, and remote control will contribute to smarter, more sustainable greenhouse management practices, ultimately improving productivity and promoting healthier crops.

This research introduces a solar-powered automatic sprayer designed specifically to address these concerns. By leveraging renewable energy, the sprayer not only reduces the environmental impact typical of conventional pesticide application methods but also promotes energy efficiency in farming operations. The user-friendly design, featuring a slider control for volume and intensity adjustments, ensures that farmers can carefully manage pesticide usage according to their crop's specific needs. The irrigation through pumps, intercultural operations, fertilizer spraying for plant protection, harvesting, and post-harvest processing, and other agricultural field activities all consume a significant amount of energy. As a result, renewable energy sources must be used to operate the aforementioned agricultural activities(Castro et al., 2024). The basic principle of a pesticide sprayer is to appropriately target the required place, which enhances the effective use of agricultural chemicals(Meshram et al., 2022). In addition to its practical features, the sprayer is integrated with a mobile application that allows users to operate the device remotely and receive health alerts regarding potential allergic reactions from chemical exposure. This dual focus on technological innovation and farmer safety aims to empower agricultural workers, improve crop protection methods, and foster a healthier, more sustainable approach to farming(Al-Okby et al., 2021; Alvarez-Perea et al., 2021; Kittusamy et al., 2025). As the agricultural industry continues to evolve, solutions like the solar-powered automatic sprayer stand at the forefront of promoting a safer and more efficient future.

The primary aim of this paper includes an intelligent greenhouse management system, which incorporates check the water level, humidity, and measure soil moisture with control primarily based on real-time area data. Making the use of intelligent and IoT techniques. The Controlling of all these duties can be via smartphone application related to the internet and the duties can be achieved via interfacing wifi modules, sensors and actuators with order to decrease the lab work and human to make cost efficient system(Bersani et al., 2022; Morchid et al., 2025). The Internet of Things arose from the widespread adoption of several relatively new information technologies, including sensor networks, automatic control, and communication. Recent technological advancements have resulted in significant progress in the fields of automatic control and communication, and the IoT is directly attributed to the advancement of thesetechnologies(Rejeb et al., 2022).

2. Literature Review

The increasing demand for food production due to a growing global population has put significant pressure on agricultural practices. Traditional farming methods often rely on manual labor and resource-intensive processes, which can lead to inefficiencies and increased operational costs(Giller et al., n.d.). In particular, the methods used for pest and disease management, such as manual spraying of pesticides, not only demand considerable physical labor but also pose health risks to farmers, including skin issues and respiratory problems caused by exposure to harmful chemicals. Additionally, these traditional methods typically require fuel for transportation and power, further contributing to environmental degradation and rising expenses. In response to these challenges, there is a compelling need for innovative solutions that can enhance agricultural productivity while minimizing health risks and environmental impacts. The Smart Greenhouse Management System leverages modern technology to

address these issues. By utilizing a Raspberry Pi for system control and monitoring, combined with solar panels for sustainable energy, this research aims to create an efficient, cost-effective greenhouse management solution that can operate independently of fossil fuels (Maraveas, 2023; Maraveas et al., 2023; Nachappa, n.d.). This system incorporates real-time monitoring capabilities, enabling farmers to keep track of essential environmental parameters such as temperature, humidity, soil moisture, and light levels. Through this innovative approach, the Smart Greenhouse Management System not only promotes agricultural efficiency but also enhances the safety and health of farmers by reducing their reliance on harmful practices associated with traditional pest management (Kabato et al., 2025). The proposed idea drives a solar powered nozzle with pump, which sprays pesticide alone with environmental benefits (Lochan et al., 2024). The proposed spraying is suitable for small and medium scale farmers. Large scale production of the spraying unit will reduce the cost and use of fuel significantly giving partial thrust to Pakistani agriculture practices (Ghafoor et al., 2022).

Implanting a smart agriculture system equipped with humidity, soil moisture and water level sensor along with automation features can lead to significant improvements in agricultural practices (Anoop et al., 2024). Big advantage of IoT is that, it reduces the amount of manual labour. The System has high efficiency and accuracy in fetching the live data of temperature and soil moisture. The IoT based smart farming System being proposed via this report will assist farmers in increasing the agriculture yield and take efficient care of food production as the System will always provide helping hand to farmers for getting accurate live feed of environmental temperature and soil moisture with more than 99% accurate results (Dhanaraju et al., 2022; Karthikeyan et al., 2021; Singh et al., 2022). This research advances sustainable farming by using modern technology such as IOT sensors and automation to optimize resource use, reduce chemical inputs, and minimize environmental impact. It helps improve crop health and resilience against climate change and pests, promoting a more responsible and eco-friendly approach to agriculture for a stronger, more sustainable future. The literature review offers a thorough analysis of the existing body of work related in the research articles. It highlights the significant contributions made by various studies, detailing their findings and the approaches they employed. Additionally, the review critically addresses the limitations and challenges encountered in these previous studies, shedding light on areas that require further exploration. Furthermore, it identifies specific research gaps that have emerged from this analysis, serving as a foundation for discussing the motivation behind the current research. This thorough assessment not only reinforces the importance of the proposed research but also sets the stage for its potential impact in the field.

The increasing health issues, much man-power and a lot of fuel usage has led to the development of smart Green House Management systems designed to reduce health issues, fuel usage and man-power (Ummak et al., 2024). These shortcomings highlight the need for more sustainable and intelligent systems that can operate with minimal human intervention while ensuring optimal environmental conditions for plant growth. The analysis of prior research clearly identifies a gap in the development of holistic solutions that address not just automation, but also the critical concerns of human health, fuel consumption, and operational efficiency. This gap forms the basis for the motivation behind the current research.

The proposed research aims to design and implement a Smart Greenhouse Management System that effectively minimizes manual labor, reduces the risk of health issues for workers, and lowers fuel consumption through intelligent automation and energy-efficient operations. By leveraging modern technologies such as IoT sensors, microcontrollers, and real-time monitoring systems, the greenhouse can autonomously regulate temperature, humidity, soil moisture, and light conditions based on plant needs. This system not only enhances crop productivity and consistency but also contributes to environmental sustainability by reducing dependency on fossil fuels and minimizing the greenhouse's carbon footprint.

2.1 Real-Time Monitoring systems:

The Smart Greenhouse Management System provides users with a comprehensive real-time monitoring solution accessible through a user-friendly mobile application(John et al., 2023; Zaguia, 2023). This app allows users to continually track critical greenhouse parameters such as temperature, humidity, light levels, and soil moisture directly from their smartphones. With the integration of advanced sensors and Raspberry Pi technology, the system not only displays current environmental conditions but also analyzes data patterns to detect potential plant diseases early on. Through real-time alerts and notifications, users can receive immediate updates on any anomalies, enabling timely interventions to ensure plant health.

The work in presented an IoT-based architecture for two Greenhouses using switched Ethernet and Wi-Fi with Networked Control Systems(Yaslam et al., 2024). Certain sensors require real-time responses within one second, and Riverbed simulations show zero packet loss or delays. A key contribution is a channel allocation scheme that reduces interference in the system. The paper also describes a fault-tolerant mechanism where, if one controller fails, the other takes over, again confirmed by simulations with no packet loss.

The automation of greenhouses, achieved through the integration of the Internet of Things (IoT) and embedded systems, addresses various challenges faced by traditional greenhouse farming. This approach enables automated control and monitoring of the greenhouse environment, reducing the need for constant oversight by farmers. The work in proposed a system that utilizes IoT technology for greenhouse automation by employing the Netduino 3 along with sensors to monitor moisture, temperature, sunlight, and humidity. The goal is to enhance production rates while minimizing the discomfort experienced by farmers(Collado et al., 2021).

2.2 Machine Learning in plant Disease Detection

In our research, we harness the power of machine learning coupled with Raspberry Pi technology to revolutionize plant disease detection. This innovative approach enables real-time monitoring and analysis of plant health through a mobile application. By utilizing a Raspberry Pi equipped with cameras and sensors, we can capture high-resolution images of plants and environmental conditions, feeding this

data into machine learning algorithms designed to identify various plant disease(Tugrul et al., 2022). Our system uses convolutional neural networks (CNNs) to analyze the images captured from plants.

These CNN models are trained on a large dataset that includes both healthy and diseased plant samples. This training helps the system learn to accurately identify and distinguish different plant health conditions, enabling early detection of diseases and supporting better plant management(Shoaib et al., 2023). This training process enables the model to recognize subtle visual cues, such as changes in leaf color, texture, and the presence of spots or lesions, that indicate potential diseases.

Once the machine learning model is deployed on the Raspberry Pi, it can operate efficiently and independently, analyzing images in real time as they are taken by the user through the mobile app(Biglari et al., 2023). The combination of Raspberry Pi technology and machine learning not only enhances disease detection accuracy but also fosters a proactive approach to plant health management(Joice et al., 2025). The application of ML and DL techniques in plant disease detection is a rapidly evolving field with promising results. While these techniques have demonstrated their potential to accurately identify and classify plant diseases. There are still limitations and challenges that need to be addressed(Gunaydin et al., 2021). Over the last decades, the foremost practiced approach for detection and identification of disease is the optic observation by consultants. However, in several cases, this approach proves impracticable to the excessive time interval and inaccessibility of consultants at farms settled in remote areas(Alemu et al., 2022).

2.3 Web Applications for Real-Time Monitoring

IoT environmental monitoring helps control infections and prevent disease outbreaks in greenhouses by providing real-time data on temperature, humidity, and other conditions. It allows operators to identify early signs of imbalance that could promote pathogens. Early detection of potential issues enables proactive interventions, protecting crops from significant damage. Overall, IoT enhances greenhouse management, promoting healthier plants and higher yields(Sharma et al., 2024).

In the authors developed a web application that serves as a centralized platform for real-time monitoring of plant health, utilizing data collected from Raspberry Pi devices. This user-friendly application features an intuitive interface where users can easily navigate through dashboards, view plant health reports, and analyze historical data trends(Sharma et al., 2024). The application provides real-time data visualization, showcasing environmental factors such as humidity, temperature, and light levels alongside health assessments derived from machine learning algorithms. Users receive timely alerts and notifications about potential disease outbreaks or environmental issues, ensuring they can take immediate action to protect their plants. Additionally, the web application logs all health assessments and environmental data over time, allowing users to track changes and evaluate treatment effectiveness.

2.4 Remote Accessibility

Our web page for real-time plant health monitoring is designed with remote accessibility in mind, allowing users to stay connected to their plants anytime and anywhere. By being web-based, the

application can be accessed from any device with an internet connection, including desktops, laptops, tablets, and smartphones. This flexible accessibility ensures that users can monitor environmental conditions and plant health status on-the-go, enabling them to respond promptly to alerts and notifications.

3. Methodology

3.1 System Overview

This study proposes a Smart Greenhouse Management System (SGHMS) that integrates embedded hardware, IoT sensors, machine learning, and renewable energy to automate crop monitoring and management. The system performs real-time environmental sensing, disease detection, and autonomous actuation, while ensuring off-grid operation through solar power. A centralized Raspberry Pi 4 serves as the core controller, orchestrating data collection, decision-making, and communication with a remote cloud server. The overall system architecture, including sensor integration, control units, cloud connectivity, and actuation mechanisms, is illustrated in Fig. 1.

3.2 Hardware Architecture

The system incorporates multiple hardware components for sensing, actuation, computation, and energy management. The Raspberry Pi 4 is responsible for acquiring sensor data, executing control algorithms, and running the image-based disease detection model. Environmental variables such as temperature, humidity, soil moisture, light intensity, and water level are monitored using appropriate sensors. The data is displayed locally and also uploaded to a Firebase cloud database. Automated actuators include a water pump for irrigation and a motorized sprayer for pesticide application. Hardware components displaying specifications used in the smart greenhouse system are mention in Table 1 (Sharma et al., 2024).

Table 1
Hardware components used in the smart greenhouse system.

Component	Specification
Raspberry Pi	Raspberry Pi 4 Model B (2GB/4GB RAM) – main control unit
Raspberry Pi Cam	8MP Camera Module – for plant image capture and disease detection
Solar Panel	12V, 20W Polycrystalline – to power the system sustainably
Stepper motor	5V or 12V Stepper Motor – for automated window or vent control
Humidity Sensor	DHT11 or DHT22 – for measuring air humidity
Temperature Sensor	DHT11 or DHT22 – combined with humidity sensing
Soil Moisture	Capacitive Soil Moisture Sensor – to monitor soil water content
LCD	16x2 or 20x4 LCD Display – to show real-time sensor readings
Water Pump	12V DC Mini Water Pump – for automated irrigation
Water Level Sensor	Float Sensor or Ultrasonic – to detect tank water levels

3.3 Environmental Sensing and Data Acquisition

Environmental conditions inside the greenhouse are monitored continuously using embedded sensors interfaced with the Raspberry Pi. The DHT22 sensor captures temperature and humidity, capacitive probes detect soil moisture, and an LDR module tracks light intensity. A water level sensor monitors tank status to prevent dry-run conditions during irrigation.

Sensor data is sampled at regular intervals and processed locally. When thresholds are crossed such as low soil moisture or high temperature automated responses are triggered. All readings are transmitted securely to the Firebase cloud for remote logging and visualization.

3.4 Plant Disease Detection

The system uses an onboard Pi Camera to capture leaf images periodically. These images are processed using a Convolutional Neural Network (CNN) model deployed locally on the Raspberry Pi. The CNN was pre-trained on a dataset of healthy and diseased plant leaves and is capable of detecting visual symptoms such as spots, lesions, or discoloration.

When a disease is detected, the system logs the event, notifies the user via the dashboard, and optionally initiates pesticide spraying. This localized detection minimizes latency and ensures consistent performance in environments with limited internet access.

3.5 Automation and Control

Actuators are controlled based on sensor data and disease detection outcomes. When soil moisture drops below a predefined level, the system activates the irrigation pump. Similarly, the sprayer

mechanism driven by a stepper motor is triggered either automatically or through manual override via the user interface. Control signals are generated using GPIO pins and managed via Python-based logic scripts.

3.6 Cloud Communication and User Interface

The SGHMS includes a real-time communication pipeline with Firebase. Sensor data and disease alerts are uploaded securely using HTTPS protocols. A web dashboard provides access to historical trends, live readings, and control toggles for users to manage the greenhouse remotely. The system supports responsive notifications to inform the user of critical changes.

3.7 Power Supply and Energy Management

To support off-grid deployment, the entire system is powered by a 12V, 20W solar panel connected to a rechargeable battery and charge controller. This setup ensures continuous availability, even during power outages or in rural regions. The Raspberry Pi and all peripherals are selected for low power consumption, maximizing the energy efficiency of the solution.

4. TESTING, RESULTS & DISCUSSION

4.1 Testing Setup and Procedure

The Smart Greenhouse Management System was tested in a controlled greenhouse environment over a continuous 30-day period. The testing setup included:

- Deployment in a 3m × 3m enclosed greenhouse.
- Installation of all sensors, actuators, and solar power supply.
- Real-time monitoring of temperature, humidity, light intensity, soil moisture, and water levels.
- Local disease detection using a Raspberry Pi-mounted camera and a CNN model.
- Data logging and dashboard visualization via Firebase.

Individual components were tested for calibration, communication, and control behavior before integrating the full system.

4.2 Performance Evaluation

Key performance metrics included sensor accuracy, disease detection performance, system uptime, and energy efficiency. Table 2 summarizes the operational status of each module during the test phase (Sharma et al., 2024).

Table 2
Operational status and performance of system modules.

Module	Function	Test Result
Raspberry Pi 4	Sensor data acquisition, processing	Functional
Soil Moisture & Temp Sensor	Environmental data collection	Stable
Pi Camera + CNN	Disease detection	92% accuracy
DC Water Pump	Automated irrigation	Functional
Stepper Motor	Controlled pesticide spraying	Functional
Firebase Cloud	Data sync and dashboard	No lag
Solar Panel + Battery	Power supply	97% uptime

The system maintained environmental monitoring with high stability. Temperature rose from 25.5°C to 27°C, while humidity declined from 55–35%. Soil moisture showed decreasing trends, triggering timely irrigation. Light intensity remained consistent. This is shown in Fig. 2.

In addition to qualitative validation, system efficiency was compared quantitatively with traditional manual practices. Key improvements were observed in energy and water usage, as well as in the rate of disease detection. This is shown in Fig. 3.

4.3 Disease Detection Results

The convolutional neural network deployed locally on the Raspberry Pi achieved 92% classification accuracy on test images. It successfully identified key symptoms like leaf discoloration and spot formation. Alerts were generated in real time, enabling prompt responses via the dashboard. The real-time plant detection system interface is shown in Fig. 4.

The system correctly identified disease in two out of three visible plants and displayed bounding boxes with confidence scores. This result confirms the system’s practical utility for early-stage plant health monitoring.

4.4 Live Interface and LCD Monitoring

Environmental readings were also displayed on-site through a 16x2 LCD module, offering an offline fallback interface. This is shown in Fig. 5.

The LCD continuously displayed environmental parameters, confirming the system’s reliability even without internet connectivity.

5. CONCLUSION & FUTURE WORK

This research presents the design and development of a Solar-Based Automated Greenhouse Management System with a focus on smart pesticide spraying and disease detection. In traditional farming practices, farmers manually spray chemicals to protect crops from pests and diseases, which can be time-consuming, labor-intensive, and potentially hazardous to human health. Our research aims to automate this spraying process using renewable energy and IoT-based remote control, reducing dependency on manual labor while improving safety and efficiency.

The system is powered by solar energy, making it environmentally and economically friendly and suitable for off-grid agricultural areas. A motorized spraying mechanism is mounted on a slider rail system that moves across the greenhouse, ensuring uniform coverage of pesticides. The movement and operation of the system are controlled remotely via a custom-developed web interface or mobile app, allowing users to start, stop, and monitor the spraying process in real-time.

This research not only helps reduce human exposure to harmful chemicals but also supports sustainable farming through automation and renewable energy. It demonstrates the effective integration of electronics, IoT, ML and solar technology to address real-world agricultural challenges.

5.1 Limitations

Despite the promising functionality and automation benefits of the solar-based greenhouse management and spraying system, several limitations were identified during its development and implementation. Power Dependency remains a concern, as the system relies on consistent sunlight for energy; cloudy weather or extended periods without sunlight may reduce operational efficiency unless a robust battery backup is integrated. Network Connectivity Issues also present challenges, as the control and monitoring features through the web page or mobile app require stable internet access, which may not be available in remote farming areas. The current design uses a fixed slider mechanism, which limits the spraying range to predefined tracks, making it less adaptable to greenhouses of varying shapes and sizes. Additionally, the lack of real-time environmental feedback such as temperature, humidity, or soil condition data restricts the system's ability to make intelligent, condition-based spraying decisions. The system's manual calibration and maintenance requirements, particularly for the motor and spraying components, may pose difficulties for farmers with limited technical expertise. Lastly, chemical handling safety remains an important consideration, as improper storage or leaks in the spraying mechanism could pose health or environmental risks.

5.2 Future Work

While the proposed Smart Greenhouse Management System (SGHMS) demonstrated effective integration of solar-powered automation, IoT-based sensing, and real-time disease detection, several areas offer potential for further enhancement. Future improvements will focus on increasing the system's adaptability, intelligence, and scalability to support broader deployment in diverse agricultural environments.

One key direction is the integration of adaptive control algorithms driven by real-time weather forecasting and crop phenology, enabling dynamic adjustment of irrigation and spraying schedules. Additionally, replacing the fixed-slider spraying mechanism with a mobile robotic platform would enhance coverage and make the system suitable for greenhouses of varying sizes and configurations.

Further enhancements may include advanced energy optimization using MPPT (Maximum Power Point Tracking) controllers and higher-efficiency solar panels to ensure reliable operation under fluctuating weather conditions. Expansion of the sensor suite to monitor additional environmental variables such as CO₂ levels, light spectra, and air quality would improve microclimate management.

From a computational standpoint, integrating edge–cloud hybrid AI models could enable more complex analytics without compromising local responsiveness. Finally, enhancing the mobile/web dashboard with multi-language support, voice commands, and AI-driven decision support tools would improve accessibility and usability, particularly for smallholder farmers in rural regions.

5.3 Conclusion

This study presents the design, implementation, and validation of a solar-powered Smart Greenhouse Management System (SGHMS) that integrates IoT-based environmental sensing, edge-deployed machine learning for disease detection, and autonomous actuation mechanisms to enable sustainable and intelligent farming. Unlike conventional systems, the proposed solution leverages Raspberry Pi–based local computation and a CNN-trained classifier to detect plant diseases in real time, triggering automated spraying through a motorized system. The integration of solar energy ensures the system's viability in off-grid and resource-constrained environments, enhancing its applicability for rural agriculture.

Through a 30-day deployment in a controlled greenhouse environment, the system demonstrated reliable performance in environmental monitoring, efficient water and energy usage, and 92% accuracy in disease detection. The inclusion of a web and mobile application interface empowers users with remote visibility and control, further improving decision-making and responsiveness.

The combination of energy autonomy, real-time plant health diagnostics, and intelligent actuation positions this system as a scalable and cost-effective solution for modern greenhouse management. It contributes to the advancement of precision agriculture, addressing key challenges in automation, sustainability, and plant health monitoring. Future enhancements may include AI-based adaptive control strategies, robotic mobility for flexible spraying, and integration with climate prediction models to further optimize agricultural outcomes.

Declarations

Funding: The British Academy/Cara/Leverhulme Researchers at Risk Research Support Grant. The University of Manchester

Conflicts of interest/Competing interests: Not applicable

Availability of data and material: Data are fully available upon request.

Code availability: Not applicable

Clinical trial number: Not applicable

Authors' contributions

1. Dilbar Hussain: Technical writing and development of scientific data analysis for the manuscript.
2. Fahiza Fauz: General methodology and mathematical modelling.
3. Turkia Almoustafa (Corresponding Author): Original idea, writing, and editing for scientific purposes.
4. Muhammad Abbas: Technical writing and overall compilation for the manuscript.
5. Zohran Rasheed: Technical writing and editing process.

References

1. Alemu, Y., & Tolossa, D. (2022). Consultation and Displacement in Large-Scale Agriculture Investment: Evidence from Oromia Region's Shashamane Rural District. *Land*, 11(9). doi: 10.3390/land11091384
2. Al-Okby, M. F. R., Neubert, S., Roddelkopf, T., & Thurow, K. (2021). Mobile detection and alarming systems for hazardous gases and volatile chemicals in laboratories and industrial locations. In *Sensors* (Vol. 21, Issue 23). MDPI. doi: 10.3390/s21238128
3. Alvarez-Perea, A., Dimov, V., Popescu, F. D., & Zubeldia, J. M. (2021). The applications of eHealth technologies in the management of asthma and allergic diseases. In *Clinical and Translational Allergy* (Vol. 11, Issue 7). John Wiley and Sons Inc. doi: 10.1002/clt2.12061
4. Anoop, E. G., & Bala, G. J. (2024). IoT and ML-based automatic irrigation system for smart agriculture system. *Agronomy Journal*, 116(3), 1187–1203. doi: 10.1002/agj2.21344
5. Bersani, C., Ruggiero, C., Sacile, R., Soussi, A., & Zero, E. (2022). Internet of Things Approaches for Monitoring and Control of Smart Greenhouses in Industry 4.0. In *Energies* (Vol. 15, Issue 10). MDPI. doi: 10.3390/en15103834
6. Biglari, A., & Tang, W. (2023). A Review of Embedded Machine Learning Based on Hardware, Application, and Sensing Scheme. In *Sensors* (Vol. 23, Issue 4). MDPI. doi: 10.3390/s23042131
7. Castro, R. P., Dinho da Silva, P., & Pires, L. C. C. (2024). Advances in Solutions to Improve the Energy Performance of Agricultural Greenhouses: A Comprehensive Review. *Applied Sciences (Switzerland)*, 14(14). doi: 10.3390/app14146158
8. Collado, E., Valdés, E., García, A., & Sáez, Y. (2021). Design and implementation of a low-cost IoT-based agroclimatic monitoring system for greenhouses. *AIMS Electronics and Electrical*

Engineering, 5(4), 251–283. doi: 10.3934/electreng.2021014

9. Dhanaraju, M., Chenniappan, P., Ramalingam, K., Pazhanivelan, S., & Kaliaperumal, R. (2022). Smart Farming: Internet of Things (IoT)-Based Sustainable Agriculture. In *Agriculture (Switzerland)* (Vol. 12, Issue 10). MDPI. doi: 10.3390/agriculture12101745
10. Ghafoor, A., Khan, F. A., Khorsandi, F., Khan, M. A., Nauman, H. M., & Farid, M. U. (2022). Development and Evaluation of a Prototype Self-Propelled Crop Sprayer for Agricultural Sustainability in Small Farms. *Sustainability (Switzerland)*, 14(15). doi: 10.3390/su14159204
11. Giller, K. E., Delaune, T., Vasco Silva, J., Descheemaeker, K., van de Ven, G., Schut, A. G., van Wijk, M., Hammond, J., Hochman, Z., Taulya, G., Chikowo, R., Narayanan, S., Kishore, A., Bresciani, F., Mancini Teixeira, H., Andersson, J. A., & van Ittersum, M. K. (n.d.). *The future of farming: Who will produce our food?* doi: 10.1007/s12571-021-01184-6/Published
12. Gunaydin, G., Gedik, M. E., & Ayan, S. (2021). Photodynamic Therapy—Current Limitations and Novel Approaches. In *Frontiers in Chemistry* (Vol. 9). Frontiers Media S.A. doi: 10.3389/fchem.2021.691697
13. John, A. E., Cletus, F., & Wajiga, G. M. (2023). Smart Monitoring System for Vegetable Greenhouse. In *International Journal of Computer Applications* (Vol. 185, Issue 34). Retrieved from www.thingspeak.com.
14. Joice, A., Tufaique, T., Tazeen, H., Igathinathane, C., Zhang, Z., Whippo, C., Hendrickson, J., & Archer, D. (2025). Applications of Raspberry Pi for Precision Agriculture—A Systematic Review. In *Agriculture (Switzerland)* (Vol. 15, Issue 3). Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/agriculture15030227
15. Kabato, W., Getnet, G. T., Sinore, T., Nemeth, A., & Molnár, Z. (2025). Towards Climate-Smart Agriculture: Strategies for Sustainable Agricultural Production, Food Security, and Greenhouse Gas Reduction. In *Agronomy* (Vol. 15, Issue 3). Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/agronomy15030565
16. Karthikeyan, P. R., Chandrasekaran, G., Kumar, N. S., Sengottaiyan, E., Mani, P., Kalavathi, D. T., & Gowrishankar, V. (2021). IoT Based Moisture Control and Temperature Monitoring in Smart Farming. *Journal of Physics: Conference Series*, 1964(6). doi: 10.1088/1742-6596/1964/6/062056
17. Kittusamy, L., & Kettimuthu, D. (2025). Green Guard Intelligent Pesticide Spraying Solutions. *Journal* 2025, 12, 12477. doi: 10.4236/oalib.1112477
18. Lochan, K., Khan, A., Elsayed, I., Suthar, B., Seneviratne, L., & Hussain, I. (2024). Advancements in Precision Spraying of Agricultural Robots: A Comprehensive Review. In *IEEE Access* (Vol. 12, pp. 129447–129483). Institute of Electrical and Electronics Engineers Inc. doi: 10.1109/ACCESS.2024.3450904
19. Maraveas, C. (2023). Incorporating Artificial Intelligence Technology in Smart Greenhouses: Current State of the Art. *Applied Sciences (Switzerland)*, 13(1). doi: 10.3390/app13010014
20. Maraveas, C., Karavas, C. S., Loukatos, D., Bartzanas, T., Arvanitis, K. G., & Symeonaki, E. (2023). Agricultural Greenhouses: Resource Management Technologies and Perspectives for Zero

- Greenhouse Gas Emissions. In *Agriculture (Switzerland)* (Vol. 13, Issue 7). Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/agriculture13071464
21. Meshram, A. T., Vanalkar, A. V., Kalambe, K. B., & Badar, A. M. (2022). Pesticide spraying robot for precision agriculture: A categorical literature review and future trends. *Journal of Field Robotics*, 39(2), 153–171. doi: 10.1002/rob.22043
 22. Morchid, A., Et-taibi, B., Oughannou, Z., Alami, R. El, Qjidaa, H., Jamil, M. O., Boufounas, E. M., & Abid, M. R. (2025). IoT-enabled smart agriculture for improving water management: A smart irrigation control using embedded systems and Server-Sent Events. *Scientific African*, 27. doi: 10.1016/j.sciaf.2024.e02527
 23. Nachappa, M. N. (n.d.). *A Fundamental Study of Digital Agriculture*.
 24. Rejeb, A., Rejeb, K., Zailani, S. H. M., & Abdollahi, A. (2022). Knowledge Diffusion of the Internet of Things (IoT): A Main Path Analysis. *Wireless Personal Communications*, 126(2), 1177–1207. doi: 10.1007/s11277-022-09787-8
 25. Sharma, K., & Shivandu, S. K. (2024). Integrating artificial intelligence and Internet of Things (IoT) for enhanced crop monitoring and management in precision agriculture. In *Sensors International* (Vol. 5). KeAi Communications Co. doi: 10.1016/j.sintl.2024.100292
 26. Shoaib, M., Shah, B., El-Sappagh, S., Ali, A., Ullah, A., Alenezi, F., Gechev, T., Hussain, T., & Ali, F. (2023). An advanced deep learning models-based plant disease detection: A review of recent research. In *Frontiers in Plant Science* (Vol. 14). Frontiers Media SA. doi: 10.3389/fpls.2023.1158933
 27. Singh, D. K., Sobti, R., Jain, A., Malik, P. K., & Le, D. N. (2022). LoRa based intelligent soil and weather condition monitoring with internet of things for precision agriculture in smart cities. *IET Communications*, 16(5), 604–618. doi: 10.1049/cmu2.12352
 28. Tudi, M., Ruan, H. D., Wang, L., Lyu, J., Sadler, R., Connell, D., Chu, C., & Phung, D. T. (2021). Agriculture development, pesticide application and its impact on the environment. In *International Journal of Environmental Research and Public Health* (Vol. 18, Issue 3, pp. 1–24). MDPI AG. doi: 10.3390/ijerph18031112
 29. Tugrul, B., Elfatimi, E., & Eryigit, R. (2022). Convolutional Neural Networks in Detection of Plant Leaf Diseases: A Review. In *Agriculture (Switzerland)* (Vol. 12, Issue 8). MDPI. doi: 10.3390/agriculture12081192
 30. Ummak, E., Turken, S., & Akin, D. (2024). Understanding Intimate Partner Violence Among Ethnic and Sexual Minorities: Lived Experiences of Queer Women in Norway. *Violence Against Women*, 30(5), 1274–1299. doi: 10.1177/10778012221147912
 31. Yaslam, M. A., & Humaish, B. (2024). *Graduate Studies Fair Fault-Tolerant Approach for Access Point Failures in Networked Control System Greenhouses A THESIS SUBMITTED BY*.
 32. Zaguia, A. (2023). Smart greenhouse management system with cloud-based platform and IoT sensors. *Spatial Information Research*, 31(5), 559–571. doi: 10.1007/s41324-023-00523-3

Figures

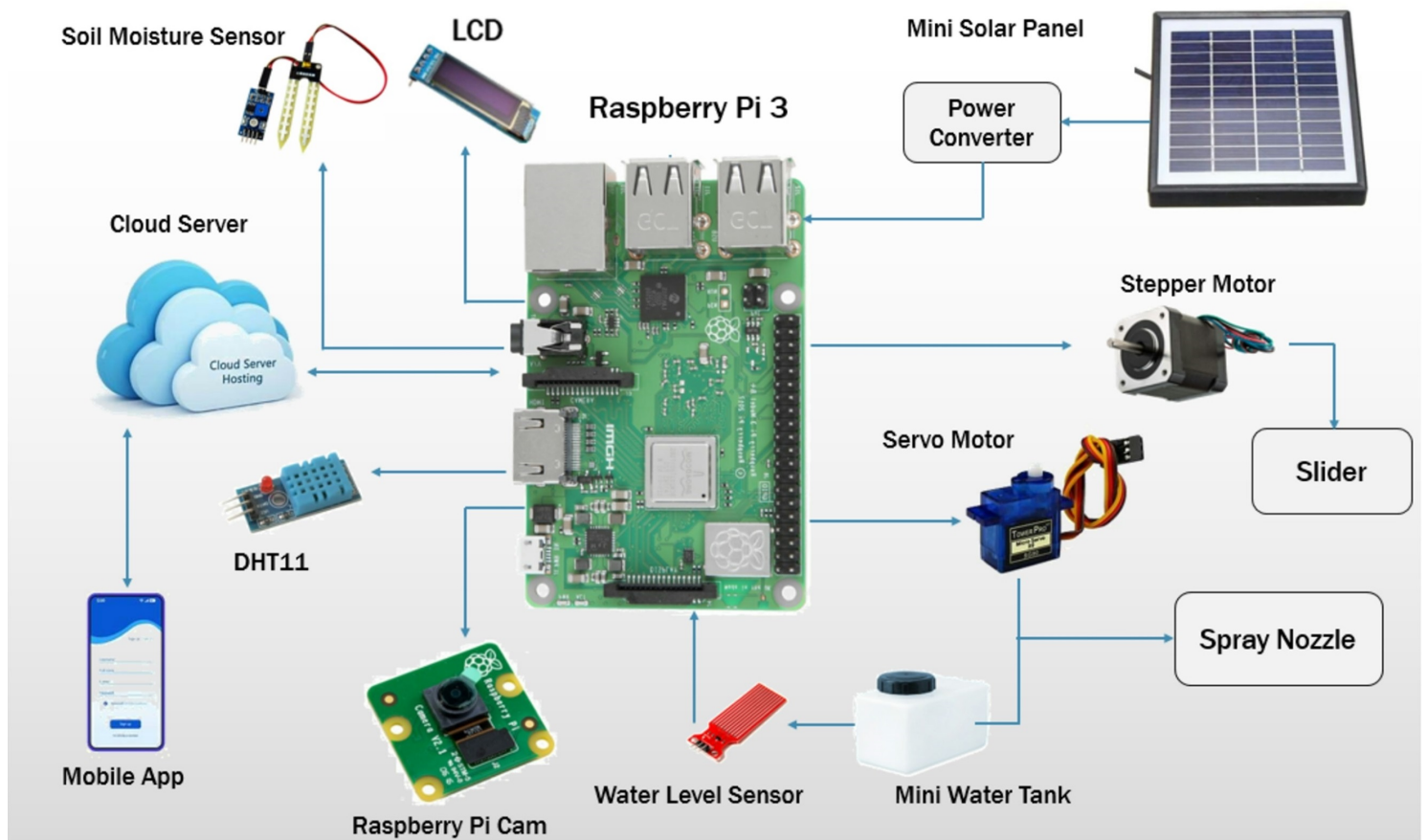


Figure 1

Overall System Architecture of the Smart Greenhouse Management System.



Figure 2

Graph of Environmental Trends During 15-day Monitoring.

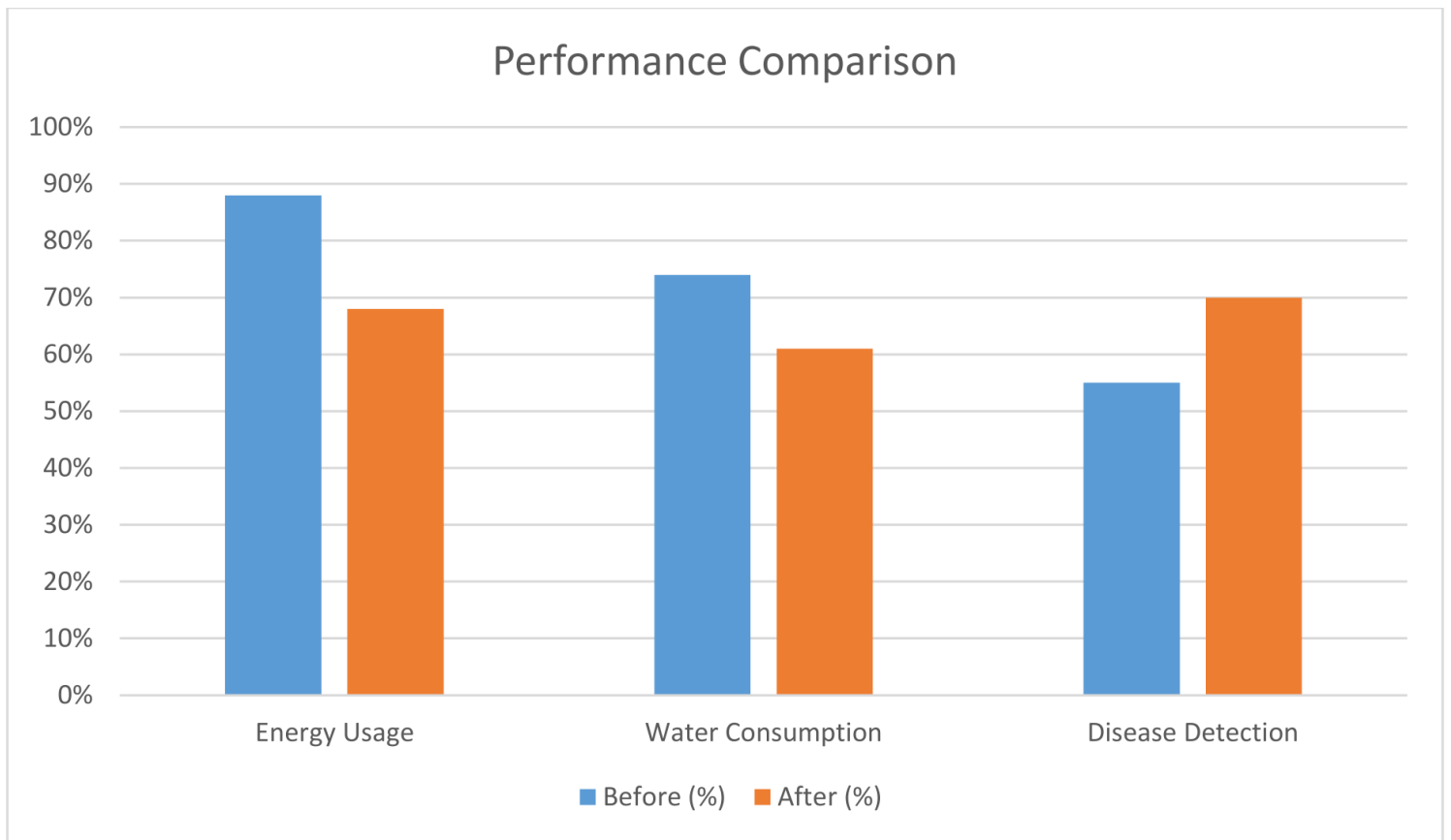


Figure 3

Comparative Analysis of Energy Usage, Water Consumption, and Disease Detection Rate Before and After System Deployment.



Figure 4

Real-time Detection of Healthy and Diseased Plants.

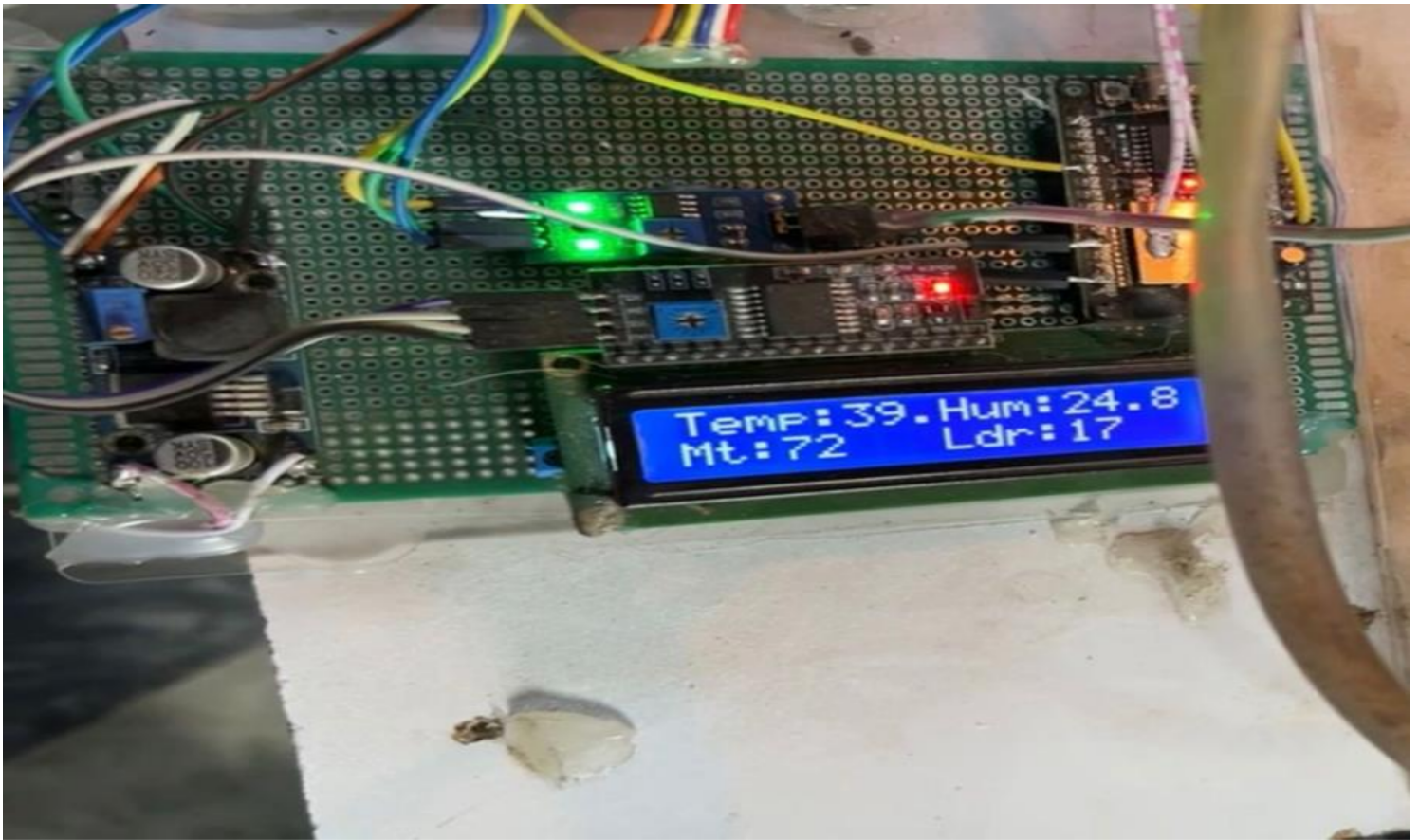


Figure 5

LCD displaying real-time temperature, humidity, moisture, and light data.