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Design and implementation of a smart solar-powered greenhouse for sustainable agriculture

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Abstract
The design and construction of the solar-powered intelligent greenhouse controller that intended to serve as a solution for sustainable farming are elaborated. The system was developed to automatically monitor and control critical environmental parameters like temperature, humidity and soil moisture which are necessary to foster healthy growth of water leaf (Talinum triangulare). The system integrated Arduino Uno microcontroller, DHT11 temperature and humidity sensor, soil moisture sensor, relay module, fan for cooling, water pump, LCD display and solar-power energy supply. Data were taken and continuously monitored with automatically controlled actuators actuated whenever any of the environmental parameters deviated from set reference. The system was tested over five days for efficiency and accuracy. The results showed that, the greenhouse was able to provide ideal environment for plant growth through control of irrigation and ventilation system. When the temperature was more than 29ºC, cooling fan was activated to lower the temperature, and water pump was actuated when the soil moisture value was less than 45%. The displayed temperature and humidity values read on LCD were also consistent with measured readings. The designed system was proven to significantly reduce manual intervention, improve utilization of resources and foster sustainable agricultural practices. Its usage on solar energy enhances the usability in remote and off-grid communities. Hence, it is a feasible, effective and environmentally friendly approach to modern agriculture.

Keywords: Smart greenhouse, Arduino Uno, solar power, temperature control, soil moisture monitoring, sustainable agriculture, water leaf cultivation, automation

Introduction

Arulmozhiyal *et al,* (2021) [4] refer to greenhouse as an agricultural structure made of glass or plastic, it is designed to protect crops from environmental hazards such as harsh climate and also create the optimal growing environment for the plant, consequently this enables an extended period of growing across diverse climate conditions 2021). With rising climate change, it threatens the state of agricultural output and food security due to impacts of rising temperatures and unpredictable weather patterns, all these can result in crop yield losses (Abou-Mehdi-Hassani *et al*, 2025).

Smart agriculture, as an important technique to combat these threats, has developed smart greenhouses to manage and control temperature, humidity, and lighting to foster plant growth, as well as reducing wastage of resources (Chen *et al*, 2025) [7]. These systems are established not only to optimize farming productivity, but also reduce reliance on chemicals and manual labour (Singh *et al*, 2024) [8].

With greater risk from farmers due to extreme weather events, adoption of resilient and data-driven farming approaches is vital (Abou-Mehdi-Hassani *et al*, 2025). Automatic greenhouse agriculture is one of the successful innovations used to sustain farming; as such can yield various types of produce such as fruit and vegetables efficiently in small areas in limited time frame (Arulmozhiyal *et al*, 2021) [4].

Smart greenhouses involve automatic control systems to govern these variables. Integrating the use of sensors, control systems, automation to improve overall efficiency and responsiveness of agriculture (Singh *et al*, 2024) [19]. This project would concentrate on the development of a solar-powered smart greenhouse to autonomously control temperature, humidity, and soil moisture for cultivation of water leaf (Talinum triangulare) since water leaf thrives at moderate temperature and humidity.

Problem Statement

Despite the use of new technologies, a number of greenhouses are operated manually leading to loss in productivity and increased risks of over-watering and non-optimal environmental conditions (Bhoi *et al*, 2022) [6]. This demonstrates an urgent necessity of developing an intelligent system capable of monitoring and controlling these key parameters in real time, without the continuous human interference (Gautam *et al*, 2024; Singh *et al*, 2024) [8].

AIMS and Objectives

AIMS

The main objective of this study is to design and build a solar powered smart greenhouse for sustainable agriculture.

Objectives

The following are the specific objectives of the project;

1. To design a smart greenhouse.
2. To fabricate a working smart greenhouse.
3. To grow water leaf under smart greenhouse conditions.

4. To conduct an experiment to analyze the smart greenhouse performance with water leaf crop.

Justification

Although agriculture has an important function in both food security and economic development, traditional agriculture methods face challenges caused by climate change and inefficient resource utilization. Manual sensing and monitoring of environmental factors, typically results in unreliable and work intensive farming practices that often leads to crop failures.

This smart greenhouse control system resolves these problems by using sensors and automation to manage an ideal growing environment for crops. This has many benefits, from increasing the number of crops produced to using resources such as water and electricity efficiently while decreasing the cost of labor. In the developing countries, such as Nigeria where food shortage is a growing problem, it offers a new and technology-based solution. Because the proposed system makes use of renewable energy such as solar power, it will be efficient and applicable to either large- or small-scale operations.

Scope of Project

The project provides an in-depth examination of the design and implementation of smart greenhouse system. Chapter 1, is the introduction of this project, it includes problem statement, objectives, importance and scope. Chapter 2, is the literature review of smart greenhouse system, discussing the growth and previous studies on smart greenhouses. Chapter 3, the design of the system and component description are explained, with specific explanation on the component requirement, system block diagrams, circuit diagrams and operating principles of the smart greenhouse. Chapter 4, implementation issues like the test conditions, limitations of this project and performance analysis were discussed. Lastly chapter 5 consists the summary of the system and conclusion drawn from the findings.

Literature Review

Historical Background

The cultivation of plants under controlled environments is not a new technology; the first instances date back to Roman times when the Emperor Tiberius, wanting his cucumbers year-round, led to farmers developing Specularia-structures for maintaining heat and providing protection to the plants at night (Rajesh *et al*, 2020) [14].

In 15th Century Asia, advanced techniques, such as Ondol under-floor heating are mentioned in agricultural texts such as the Korean Sanga Yorok (Rajesh *et al*, 2020) [14].

17th to 18th Century Europeans developed Orangeriestall masonry structures with south-facing glass windows to preserve delicate fruit trees from frost during winter. These techniques were brought to North America and utilized for agriculture and research purposes (Rajesh *et al*, 2020) [14].

Greenhouses technology continued to develop in the 19 th century with advancements in iron framework construction and industrial manufacturing of glass. In 1840 and 1842-1846, some notable greenhouse construction was produced, such as the conservatories at Cheswick and Regent's Park.

Modern greenhouse development has evolved with features like plastic coverings, automation systems for watering and ventilation, along with environment sensors. Greenhouses today rely on IoT devices, intelligent controls and automation systems to effectively maintain environmental conditions and utilize agriculture in innovative and productive ways (Hosny *et al*, Lu, 2025) [10].

Related Work

Modern greenhouses have advanced greatly from purely manual operation to being almost completely automated. Historically the automation required by manual greenhouses did not support effective upscaling of technology (Hosny *et al*, 2025) [10]. The first advances to greenhouses from Hosny *et al*. (2025) [10] allowed for the collection of data via sensors and automation of the monitoring and control of temperature, humidity, light and soil moisture. While this technology significantly reduces labor requirements and increases stability within the growing environment, it often relies on simple on-off signals that fluctuate the climate rapidly. This semi-automated type greenhouse has since advanced greatly through the incorporation of IoT as observed by Asane *et al*. (2025) [5]. Through IoT sensors collect real-time environmental data and upload it to the cloud where sophisticated algorithms automate irrigation and climate control while allowing for remote monitoring of the system. This paradigm shift allows for efficient use of resources and increased crop production and allows for the greenhouse to be monitored from any location. A model for the modern smart greenhouse developed by Zhong *et al*. (2024) [23] shows the incorporation of machine learning and data analysis techniques to create self-regulating climate controls. The algorithms are capable of adaptive and predictive control systems, reducing energy and water use. As seen by Verdouw *et al*, (2021) [21] current advances in greenhouse technology have incorporated digital twins. Digital twins can act as virtual models of a greenhouse system in order to collect data and make prediction in regard to resource usage or the performance of plants within the greenhouse. Autonomous greenhouse operations relying on predictive data collection significantly reduce waste and increase accuracy. Energy supply to a modern, smart greenhouse is an important consideration. According to Riahi *et al*. (2021) [18] solar powered, DC microgrids provide sufficient continuous energy to operate sensors, actuators, and control systems, especially in areas where stable electricity cannot be guaranteed.

Methodology

This section will describe how the Smart Greenhouse Control system has been designed and developed. A phased approach is taken through the system development, including system design, hardware components selected and assembled, and software designed and written.

System Design

TheSmart Greenhouse Control System is designed to automatically control environmental parameters such as temperature, humidity, and soil moisture using sensors and actuators which is supervised by the microcontroller in order to maximize the growing conditions of the water leaf plants. It is equipped with an LCD display unit to provide user friendly monitoring on the environment while some sensor readings and actuator conditions being controlled by the system. A water pump and a cooling fan were utilized to control the temperature and humidity at optimal conditions respectively.

The requirements for designing this system were based on the required optimal temperature, which is the range from 25-32C and the optimum relative humidity should be 60-80%. If the level of moisture in soil decreases to the minimum level, the water pump will be activated by the system so as to ensure the watering process of the water leaf plant. In the case where the temperature or the relative humidity are below the set range, the cooling fan is activated by the system so as to be kept under a reasonable temperature and humidity for the water leaf plant. Environmental readings were being displayed on an LCD panel for the users.

A DC power source is also used in the system. It is powered by using a solar energy as this system makes use of solar energy and it is reliable, efficient and eco-friendly as well as the continuity of system functioning is ensured especially in the areas like rural side where this water leaf plants is mostly being cultivated.

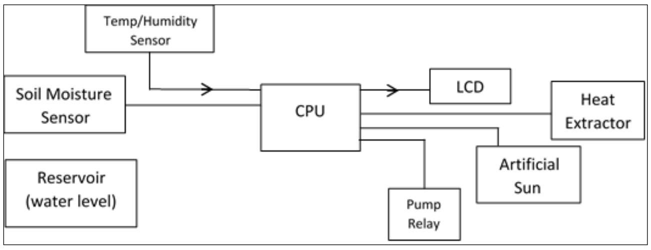

Fig 1: Block Diagram of the Smart Greenhouse Control System

System Components

The main elements that comprise the Smart Greenhouse Control System are:

1. Microcontroller (Arduino Uno R3): Serves as the brain of the system, taking in sensor inputs and processing signals and operating actuators.
2. Temperature and Humidity Sensor (DHT11): Monitors microclimatic parameters within the greenhouse, triggering the fan and pump accordingly to keep a water leaf growing optimum.
3. Soil moisture Sensor (Capacitive Type): Detects and reports on soil water level, thereby powering up the water pump only when required.
4. LCD display (16x2): Provides a direct feed for displaying the temperature, humidity, and soil moisture readings.
5. Water pump and Relay module: Activates a pump to water the plants automatically if the soil dries.
6. Fan: A DC fan, which switches on when the ambient temperature goes beyond the threshold value in the greenhouse.
7. DC Power Supply with Solar integration: Supports power generation from renewable energy source.

Component Selection

Component choices were guided by criteria such as availability, energy efficiency, reliability, and compatibility with the Arduino platform.

- **Arduino Uno R3:** Chosen for its simplicity, versatility, and broad sensor integration capabilities.

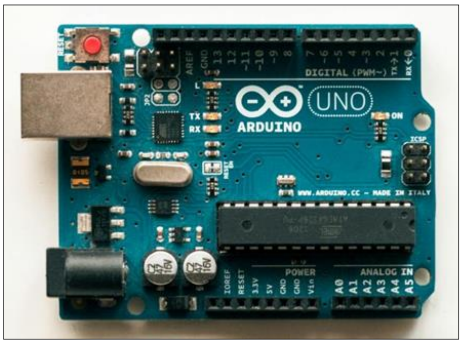

Fig 2: Arduino Uno R3 Microcontroller board

- **Temperature and Humidity Sensor (DHT11):** Selected for its accuracy, low energy consumption, and straightforward connectivity with Arduino.

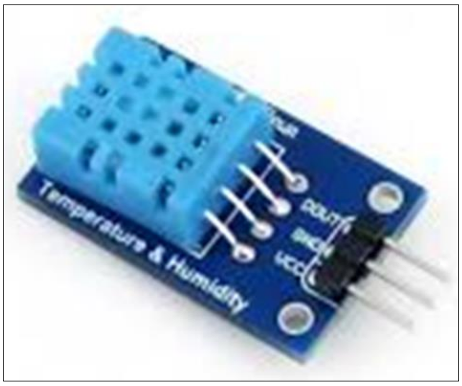

Fig 3: Temperature and Humidity Sensor

- **Capacitive Soil Moisture Sensor:** Preferred for its durability and corrosion resistance compared to resistive types.

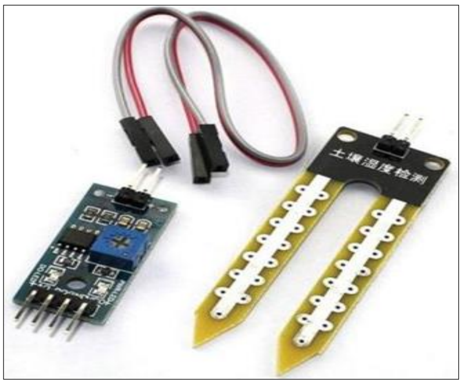

Fig 4: Resistive Soil Moisture Sensor

- **16x2 LCD Display:** Opted for its clarity, low power usage, and effectiveness in displaying multiple parameters.

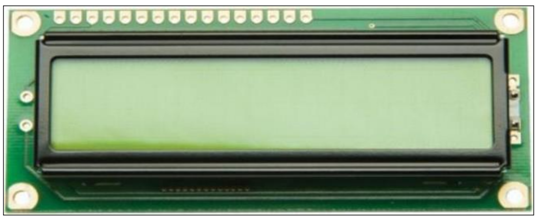

Fig 5: 16x2 LCD Display

- Relay Module: Utilized for safe switching of high-power devices like pumps and fans.

Fig 6: Relay Module

- **Solar Power System:** Chosen to ensure sustainability and functionality in off-grid regions.

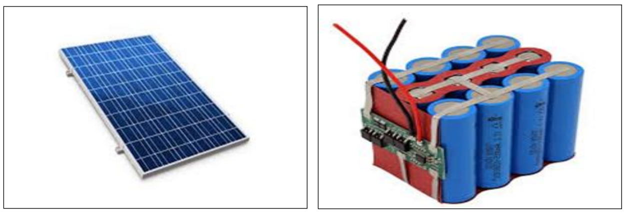

Fig 7: Solar Panel and Lithium Ion Battery

Circuit Design

The design of the circuit primarily centers around the Arduino Uno microcontroller that acts as the controller within the system. Analog pins from the microcontroller were connected to various sensors. Digital pins from the Arduino were used to control (via relays) both the pump and fan. The I2C communication protocol was used to interface the LCD to the Arduino so as to minimize the pin count required for its integration.

In order to verify the operation of the circuit, all components were initially put together on a breadboard. This was helpful in order to make suitable adjustments to the circuit. Once tested on the breadboard the circuit was permanently fixed to a box.

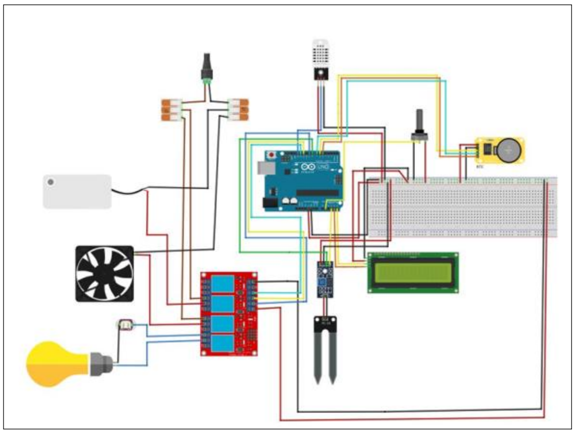

Fig 8: Circuit Diagram of The Smart Greenhouse Control System

System Operation Principle

Once powered on, the microcontroller regularly collects information from the temp, humidity and soil moisture sensors. It runs on the following logic:

1. Soil moisture < threshold then, the water pump will be turned on by the microcontroller until the moisture level returns to the threshold level.
2. Temperature > limit then, the cooling fan will be turned on.
3. LCD displays real time temp, humidity and soil moisture of the environment.

Contribution to Knowledge

The current existing knowledge in agricultural automation is enhanced by this project as we present a low cost smart solar power greenhouse controller system which has the capability of monitoring the environment and controlling the temperature, humidity and soil moisture content, thereby regulating irrigation and ventilation to the optimal level for the plants to grow.

The novelty of this project compared to traditional grid powered or manually operated greenhouse systems is that it proposes a renewable energy source and ensures continuous functioning at off-grid, rural environments. Integrating solar power and Arduino enabled system make the system affordable, sustainable and affordable for a small farmer. This system is an example of successful implementation of embedded systems and renewable energy for smart agriculture and sustainable practices.

Testing and Result Analysis

This section discusses the results obtained from the execution and testing of Smart Green House Control system. System performance with respect to monitoring and control of temperature, humidity and soil moisture was investigated to provide the best condition to plants growth.

After constructing the circuit and programming, this prototype was test for 5 continuous days in order to estimate the performance, stability and responsiveness. This test was performed in the green house condition and evaluated on how system maintains the temperature, humidity and soil moisture using sensors and actuators, which include fan and water pump.

In the test, the reading of system was taken on certain time interval in order to determine the system performance upon environment change. It was concluded from the reading that the system was able to control the water leaf plant conditions by switching on required actuator in correct situation.

Summary of control logic:

Fan: If temperature<= 29°C Fan=OFF, If temperature> 29°C Fan=ON

Water Pump: If moisture< 45% Water Pump=ON, If moisture=100% Water pump=OFF

Humidity: 60-80%

System Testing and Results

Table 1: Daily System Test Result for 5 Days

Day	Temperature (°C)	Humidity (%)	Soil Moisture (%)	System Response
1	29.0	72	55	Fan OFF, Pump OFF
2	33.5	63	42	Fan ON, Pump ON
3	30.2	78	58	Fan ON, Pump OFF
4	28.5	61	40	Fan OFF, Pump ON
5	31.0	69	50	Fan ON, Pump OFF

LCD Display Output

The LCD was capable of displaying the current readings for humidity, temperature, and soil moisture during testing and values were being read every few seconds with good accuracy which confirmed that the microcontroller and LCD were communicating.

Analysis of Results

From the test results it can be seen that the Smart Greenhouse Control System is able to monitor environment within the greenhouse. DHT11 is capable to detect variations in the temperature and humidity. Soil moisture sensor is able to detect low moisture level, below 45%, the device was activated whenever the moisture drops below that limit and was highly responsive on days 2 and 4. The cooling fan turned off on day 1 and day 4 when the temperature was below and at 29c, whereas it was turned on day 2, 3 and 5 when the temperature was above 29c. Both the cooling fan and water pump were able to receive sensor notifications immediately without any considerable delay, hence, prove that the operation with the relay is precise.

Performance Evaluation

The evaluation of Smart Greenhouse Control System was carried out based on the precision of the sensors used, system reliability and response rate. The DHT11 sensor obtained the temperature within 2 C error and humidity within 5% error, and soil moisture sensor has an error of 3%. The relay module was functional in activating water pump and cooling fan under specified condition. The LCD screen displayed the continuously updated reading on ambient condition in good display during testing without any errors. The system ran continuously without any malfunction for the five days testing duration and also was able to response to changes on the environmental variables.

Discussion

The results from the trial period show that the Smart Greenhouse Control System is able to significantly reduce the need for operator control through automated management of environmental factors. Plants were effectively watered and adequate temperature conditions were maintained as the system responded to changes in soil moisture levels and external temperature levels. It was also clear that the sensors, relay module and LCD display were all functioning together as they provided reliable information on the relevant conditions within the greenhouse, along with an effective means of automated control for watering and the fan. Although the relay's activation was slightly delayed, it did not interfere with the efficiency of the system overall. In conclusion, the system is both effective and reliable; however future development should consider implementing more sensitive sensors or possibly a notification system that alerts the user to conditions beyond a set range.

Conclusion and Recommendation

Conclusion

The Smart Green House Control System was designed, developed, and implemented as designed. The control system monitors and automatically controls the environmental variables of temperature, humidity and soil moisture within the green house while automatically controlling the fan and water pump. The data from the sensors was also transmitted to the LCD display accurately and shows that all the sensors are integrated to the system perfectly. During the test that lasted for 5 days, the system showed rapid response when there were some changes in the environment and reduces a lot of effort that had to be manually operated, hence increases the efficiency. Hence, the Smart green house control system satisfied the goals. The smart green house control system demonstrates the application of automation in modern agriculture and offers reliable and efficient greenhouse environment management. The system increases the efficiency and productivity of the greenhouses through reduced manual inputs and optimization of the growing conditions. It has a lot of potential to be upgraded to control even larger farming operation and can be integrated with smart agri-tech solutions in the future.

Recommendations

Further system enhancements for improved system operation and overall system applications are suggested:

1. Long term monitoring tests to evaluate system reliability over changing environment.
2. Higher precise sensors for the accurate environment measurements.
3. Remote sensing with IoT or GSM module.
4. Data logging capability for tracking environmental changes over time and system performance.

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