

## Design, Construction, and Testing of a Solar-Powered Automatic Plant Irrigation System

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### Abstract

Water scarcity presents a significant challenge in agriculture, making the development of efficient irrigation systems essential to optimize water use and enhance crop yields. Manual irrigation methods are labor-intensive, time-consuming, and tend to waste water through inconsistent application. This study explores the design, construction, and testing of a solar-powered automatic irrigation system using the ATmega328P microcontroller. The system combines soil moisture sensors, a relay module, and water pumps to automate watering based on real-time soil moisture data. Simulations and experiments on sandy, clay, and loamy soils confirmed the system's reliability and stable connections. Results showed that sandy soil needed the most frequent watering, 3 to 4 times daily, due to quick drainage, while clay and loamy soils required 1 to 2 and 2 to 3 activations per day, respectively. Sandy soil also responded fastest (5-10 seconds), compared to clay (15-20 seconds) and loamy (10-15 seconds). Temperature readings peaked in sandy soil (30 °C), followed by loamy (26 °C) and clay (25 °C). Flow rates were highest in sandy soil (65 cl/h), with clay and loamy soils at 50 cl/h and 12 cl/h. Relative humidity and moisture content were lowest in sandy soil (62% and 22%) versus clay (80%, 39%) and loamy (72%, 32%). Overall, the system responded quickly, operated reliably, and distributed water efficiently. The findings confirm that integrating microcontrollers and moisture sensors provides a cost-effective, scalable, and sustainable solution for precision agriculture.

**Keywords:** Automatic Irrigation System, ATmega328P Microcontroller, Soil Moisture Sensors, Soil type, Water Scarcity

### 1.0 Introduction

Water scarcity presents a major global challenge, especially for agriculture, which uses a large portion of the world's freshwater [1]. Solving this problem requires sustainable irrigation methods that improve water efficiency and crop yields. Traditional irrigation systems are labor-heavy, inefficient, and tend to overwater or underwater, damaging soil health and plant growth. To address these issues, automated irrigation systems driven by microcontroller technology, like the ATmega328P, provide a promising solution. These systems employ sensors to monitor soil moisture, temperature, humidity, and water flow, allowing for data-based irrigation scheduling. By only activating

irrigation when needed, such systems reduce water waste, enhance energy efficiency, and promote plant health [2,3].

The ATmega328P microcontroller is perfect for agricultural automation because of its low power use, versatility, and ability to work with many sensors and communication protocols [4]. It supports data processing and exact control of irrigation parts, including the water pump and relay modules. When combined with environmental sensors, it allows for site-specific irrigation based on actual field conditions, promoting optimal water use and sustainable farming practices. This automation lowers labor needs, operational costs,

and reliance on manual irrigation, especially in large-scale farming [5].

Environmental and system parameters crucial for effective irrigation include soil moisture, relative humidity, temperature, water flow rate, system response time, and pump activation frequency [5]. These variables are monitored continuously to ensure precise irrigation, boosting crop yield and conserving resources [6,7]. Additionally, integrating the system with solar panels reduces dependence on fossil fuels and promotes eco-friendly farming. Beyond technical advantages, the system empowers farmers through skill development and encourages digital literacy in agriculture, supporting global goals for sustainable development and climate resilience.

## 2.0 Materials and Methods

### 2.1 Description of the System

The solar-powered irrigation system was built using locally sourced, cost-effective materials. A protective enclosure was constructed to house the main control components, including the ATmega328P microcontroller, battery, and solar charge controller. This structure was mounted on a frame near the crop field. A solar panel, installed above the control unit, ensured continuous energy collection during the day. The water pump and relay module were placed in a separate enclosure,

connected via water tubing to the target crop area. Moisture sensors were inserted at the root level for precise soil condition readings. An LCD display on the front panel provided feedback on soil moisture. After assembly, the system was powered and tested for durability, as shown in Plate 2.1.



**Plate 2.1:** Shows the solar-powered irrigation system during field testing

### 2.2 Sources of the Materials

All components used for the construction of the solar-powered irrigation system were selected based on availability, reliability, and compatibility with the system design. The components were sourced from local electronic markets and tested individually for functionality before integration.

**Table 2.1: Materials and Components**

Components	Specifications
Microcontroller (ATmega328P)	8-bit AVR, 32 KB flash, 16 MHz, supports I/O
Soil Moisture Sensor	Analog output (0–1023) detects soil dryness for irrigation.
Temperature & Humidity Sensor	Monitors -40°C to 80°C, 20–90% RH
Solar Panel	Power source, a 10–20W panel charges a 12V battery via a controller.
Relay Module	5V module, switches up to 10A at 250V AC
LCD Display	16x2 LCD, displays moisture/status, 5V
Voltage Regulator (Buck Converter)	A step-down DC-DC converter maintains a 5V output from a higher voltage
Insulated Casing	Protective, weather-resistant enclosure for housing and insulating control components.

### 2.3 Circuit Description

The system integrates input sensors, a power supply, a control unit, and a pump control mechanism. The ATmega328P microcontroller receives analog input from the soil moisture sensor

and monitors values against pre-defined thresholds. When moisture levels fall below the set limit, the microcontroller triggers the water pump through a relay module. The pump operates on 12V DC supplied by a battery charged via the solar panel. The voltage from the battery is stepped down to 5V

using a buck converter to safely power the microcontroller and other components. The entire circuit was first assembled on a breadboard for testing and validation. After successful testing, it was transferred to a printed circuit board (PCB) for

permanent installation. The complete setup is housed in an insulated casing to protect it from environmental factors. The system circuit is shown in Plate 2.2.

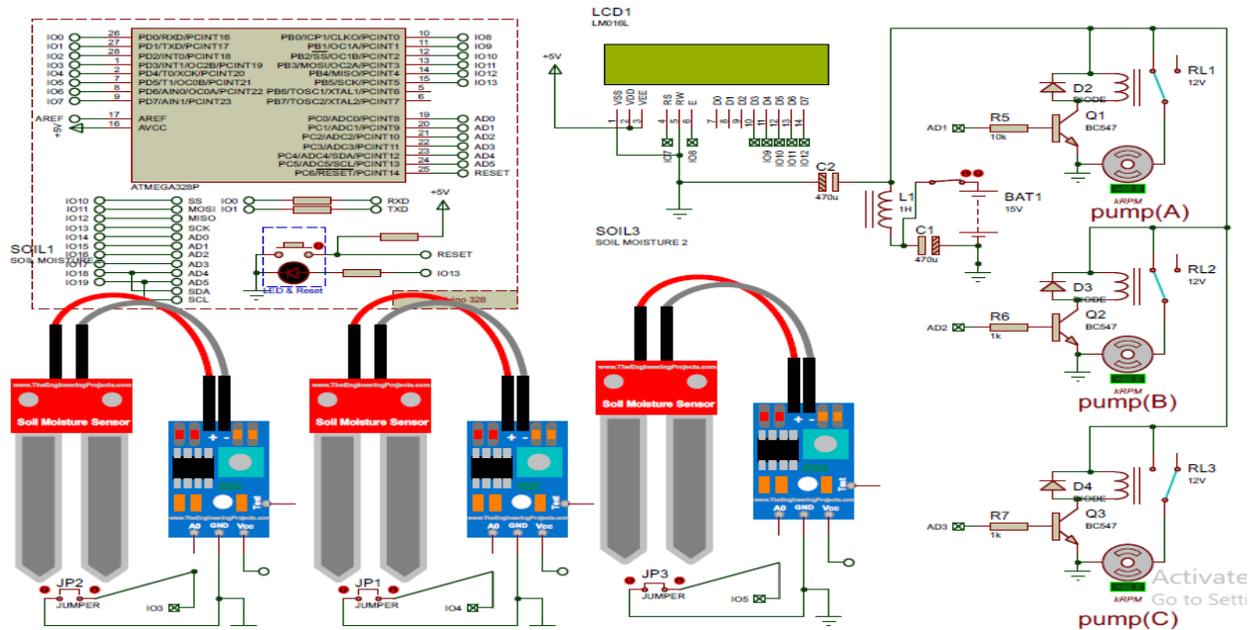


Plate 2.2: Block diagram and wiring of the irrigation system circuitry

## 2.4 Software Design Using Simulation

The software was designed and simulated using Proteus 8.13 for circuit simulation, while the Arduino IDE was used for code development and uploading. The Arduino programming environment, compatible with the ATmega328P microcontroller, provides a user-friendly interface for developing and debugging code. The Proteus software allowed for visualization and simulation of sensor responses and actuator triggers [8].

Steps involved in simulation and design included:

1. Launching Proteus and creating a new project for system design
2. Selecting ATmega328P as the primary controller
3. Building the schematic layout with moisture sensors, LCD, pump, and solar module
4. Defining I/O terminals and simulating soil dryness response
5. Uploading code via a hex file and validating system behavior using values

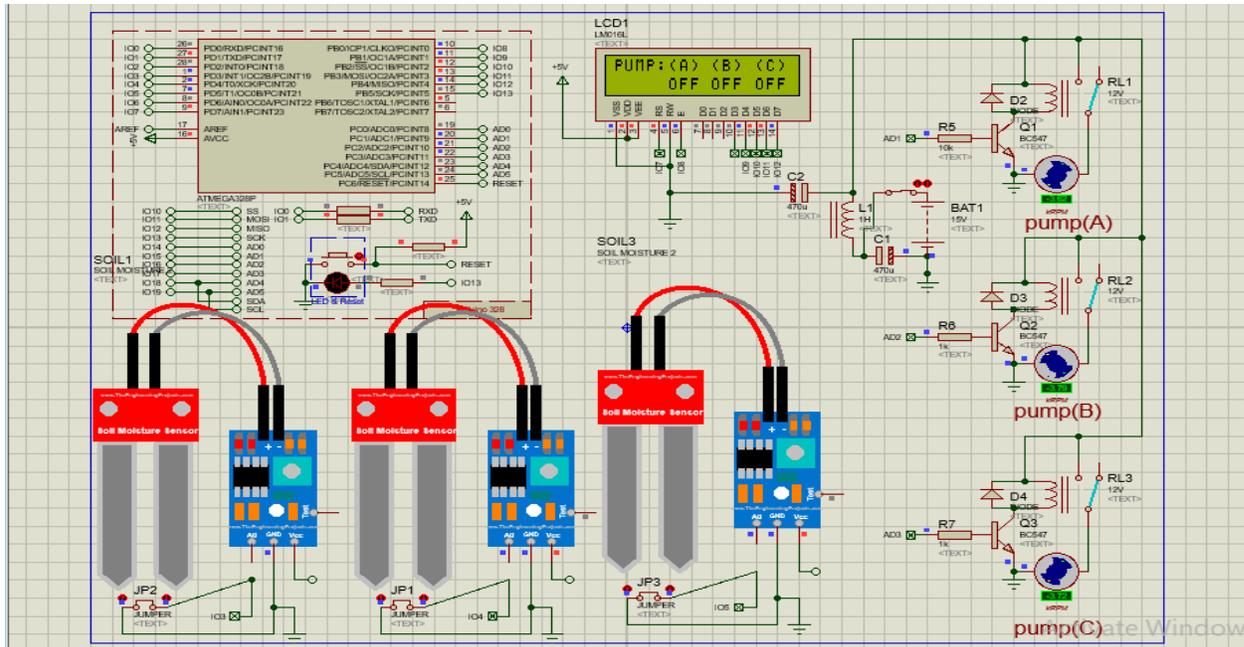


Plate 2.3: Proteus simulation interface showing connected modules

## 2.5 Design and Development of the System

The system was developed to ensure operational reliability, low power consumption, and prompt responsiveness to soil moisture conditions, in line with smart irrigation principles described by Sharma et al. [9]. The control logic embedded in the ATmega328P microcontroller continuously evaluates the moisture sensor input to determine the need for irrigation. When soil moisture content falls below the predefined threshold of 30%, the system activates the water pump to irrigate the field until sufficient moisture is restored. In addition to moisture monitoring, the sensor module records ambient temperature and humidity for environmental assessment. A solar panel powers the system by charging a 12V battery during daylight hours, providing energy for continuous operation. This configuration enables autonomous, off-grid

deployment, making it particularly suitable for remote or rural agricultural settings lacking conventional power infrastructure.

## 2.6 Development of Hardware

The hardware development phase included the construction of the system casing, installation of soil sensors, and integration of electronic components within a water-resistant enclosure. Stereotype foam was used as an internal lining to insulate the circuitry from environmental stressors such as heat and moisture. This protective measure ensured durability and extended the system's functional life under field conditions. Following assembly, the complete setup was deployed in a small garden plot to assess real-world performance. The outcome, shown in Plate 2.4, confirms the design's practicality for smallholder farms.



**Plate 2.4:** Fully assembled and deployed solar irrigation system

## 2.7 Testing Procedure

Following the design and construction of the solar-powered automatic irrigation system, a thorough testing procedure was conducted to ensure its optimal performance and reliability. All components, including the ATmega328P microcontroller, soil moisture sensors, relay module, and water pump, were individually tested for functionality. The microcontroller was programmed using the Arduino IDE. A test code was uploaded to verify serial communication, and sensor inputs were confirmed through feedback on the serial monitor. Continuity tests were conducted using a digital multimeter to check the integrity of electrical connections between power lines, analog and digital pins, and sensor interfaces. The soil moisture sensors were inserted into different soil samples, and their readings were observed to assess accuracy and consistency. The relay module was tested by simulating dry soil conditions; it responded by switching the pump on and off appropriately when the sensor readings crossed the preset moisture threshold. The fully assembled system was then evaluated in practical soil conditions: sandy, clay, and loamy soils. Moisture levels were monitored to determine the point at which the system would activate irrigation. The irrigation system responded promptly when the moisture content dropped below a set threshold, activating the water pump and ceasing operation management.

once sufficient moisture was restored. Observations showed a rapid response time of approximately 2 to 3 seconds, consistent relay switching, and stable overnight performance. These outcomes confirmed the functional accuracy and operational stability of the system, indicating its suitability for precision irrigation in varying soil environments [4,5].

## 3.0 Results

### 3.1 Result of System Simulation

The simulation confirmed the functional performance of an automatic plant watering system developed to improve irrigation efficiency through soil moisture monitoring. The system integrates soil moisture sensors, an ATmega328P microcontroller, and water pumps, which are programmed to initiate irrigation when soil moisture levels fall below a predefined threshold. This approach promotes water conservation by minimizing excess usage. The microcontroller interprets sensor inputs to regulate pump activity for individual plants, while an LCD module displays updates on soil conditions and system performance. Under both dry and wet conditions, simulation outcomes indicated that pumps A, B, and C responded appropriately by switching ON or OFF based on moisture readings, thereby validating the system's automated control mechanism and its potential for effective water management.

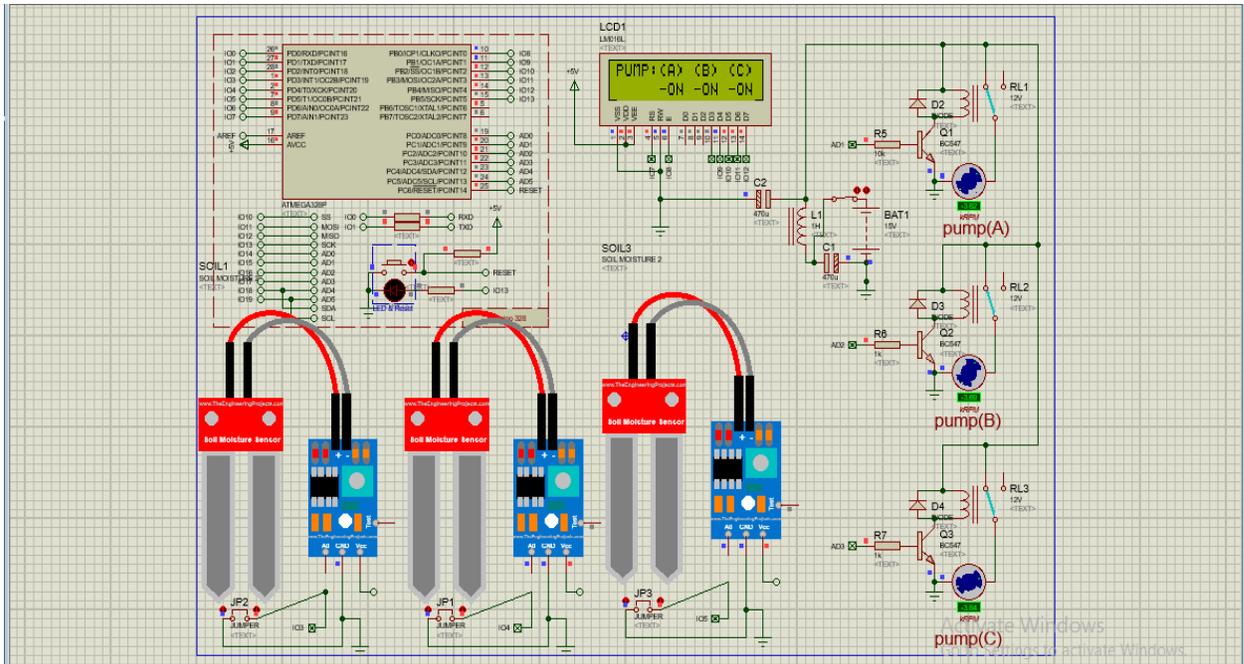


Plate 3.1: Results of the simulation of the automatic irrigation system conditions under dry conditions

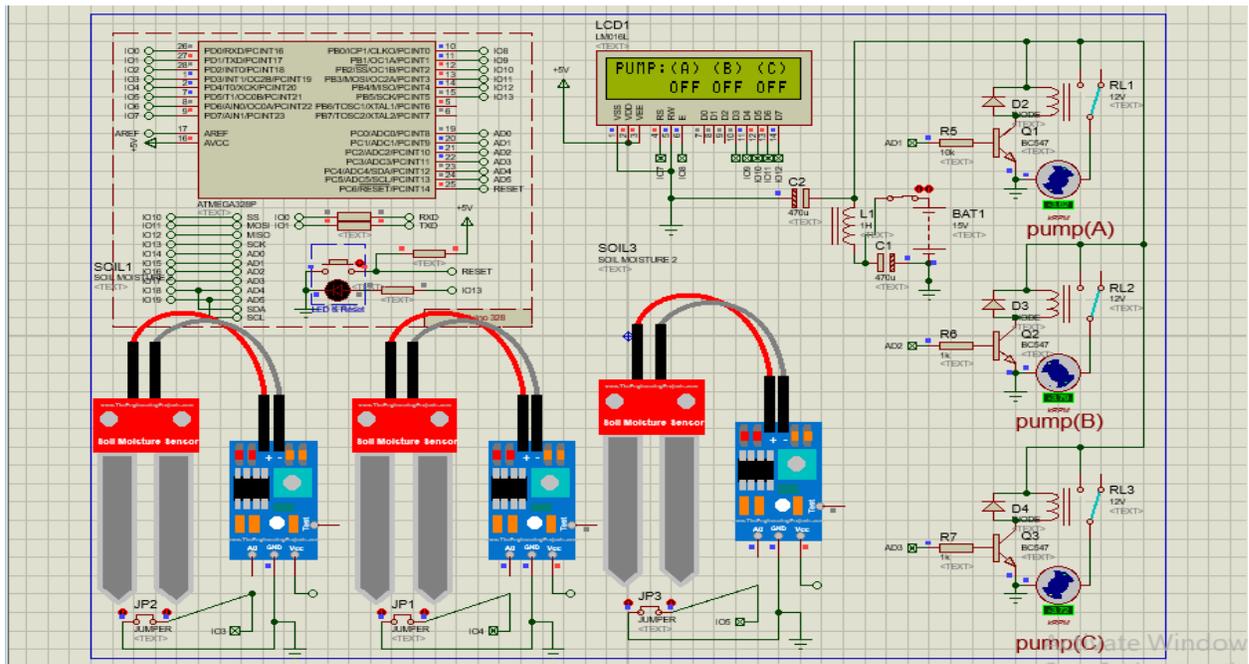


Plate 3.2: Results of the simulation of the automatic irrigation system conditions under wet conditions

### 3.2 Result of Component Testing

The result of the functionality test of the microcontroller, soil moisture sensors, relay, and electrical connections is presented in Table 3.2. As presented in Table 3.2, the functionality tests demonstrated that all system components, namely the microcontroller, soil moisture sensors, relay module, and electrical circuitry, operated effectively. Each component was individually

tested, with no electrical faults observed. The microcontroller accurately processed input signals and communicated appropriately with peripheral devices. The soil moisture sensors produced consistent and reliable data, while the relay module responded as expected by activating the water pump based on sensor feedback. These results confirm the operational integrity and readiness of the system for full deployment.

**Table 3.2:** Result of Component Functionality Test.

Component	Test Result	Status	Notes
Microcontroller	Pass	Functional	ATmega328P processed data and controlled pumps effectively
Soil Moisture Sensors	Pass	Accurate and Consistent	Provided real-time data based on soil conditions
Relay Module	Pass	Functional	Controlled the water pump in response to sensor feedback
Electrical Connections	Pass	Stable	No shorts; all connections intact

### 3.3 Continuity Test Results

The result of the continuity test presented in Table 3.3 verified that all the points tested have passed the test. The continuity test ensured all electrical connections were intact without accidental short circuits. Using a multimeter, the test confirmed the following: Ground (GND) Connections: The multimeter beeped consistently, verifying continuous ground connections between the Microcontroller, sensors, and relay. VCC

Connections (Power Rail): A beep confirmed that the power lines were correctly connected to the Microcontroller, sensors, and relay module. Analog and Digital I/O Pins: The connections from the ATmega328P's analog pins (A0, A1, A2) to the sensor input pins were verified, as well as the digital pin (Pin 8) controlling the relay module. The test confirmed that there are no wiring issues or shorts, confirming that all connections were properly established.

**Table 3.3:** Result of the Continuity Test

Connection Type	Test Points	Result	Tool Used	Notes
Ground (GND) Connections	Microcontroller to Sensors and Relay	Pass	Multimeter	Continuous ground paths verified
VCC (Power Rail) Connections	Power Lines to Microcontroller, Sensors, Relay	Pass	Multimeter	Power distribution confirmed without issues
Analog I/O Pins	A0, A1, A2 to Sensor Inputs	Pass	Multimeter	Analog signals are transmitted without interruption
Digital I/O Pins	Pin 8 to Relay Module	Pass	Multimeter	Digital control signals verified
Overall Wiring	All Electrical Connections	Pass	Multimeter	No accidental short circuits were detected

### 3.4 Functionality Test Results

The result of the functionality test for the overall system is presented in Table 3.4. The functionality tests confirmed that the automatic irrigation system operated as designed. Sensor readings accurately differentiated between dry and wet soil, triggering pump activation when moisture dropped below the

threshold. The pump deactivated once adequate moisture was restored, validating the control logic. Water delivery was smooth, and the system responded within two seconds to soil moisture changes. Stability testing showed continuous overnight operation without malfunctions, confirming system reliability.

**Table 3.4:** Result of Functionality Test of Overall System

Test	Dry Soil Result	Moist Soil Result	Unit	Notes
Moisture Sensor Readings	Low (15)	High (45)	-	Low values for dry soil and high values for moist soil, displayed on a monitor
Pump Activation	Active (Below 30)	Inactive (Above 30)	-	The pump was activated below the moisture threshold and deactivated above it.
Water Delivery	100 ml/min	150 ml/min	ml/min	Water is delivered smoothly to plants through tubing
System Response Time	2 seconds	2 seconds	Seconds	Prompt response to moisture changes
System Stability (Overnight)	Stable	Stable	-	No malfunctions or unexpected behaviour detected.



**Plate 3.3:** Moisture Sensor Functionality Test

### 3.5 Result of Experimental Test of Complete Irrigation System

The results of experimental tests of the complete irrigation system are presented in Table 3.5. The percentage soil moisture, relative humidity and temperature, water flow rate, response time, and pump activation with regard to sandy, clay, and loamy soils were observed.

The results show differences in the water-related characteristics of sandy, clay, and loamy soils. Sandy soil, with low moisture retention (12-22%), high flow rate (50-62 cl/h), low humidity (52-62%), and high temperature (26-30°C), requires the most

frequent irrigation (3-4 times/day) due to quick drainage and rapid moisture loss. Clay soil, with high moisture retention (28-29%), low flow rate (32-50 cl/h), high humidity (71-80%), and cooler temperatures (22-25°C), needs less frequent irrigation (1-2 times/day) but risks waterlogging and slow response time (15-20s). Loamy soil demonstrates balanced properties moderate moisture retention (21-32%), flow rate (9-12 cl/h), humidity (60-72%), temperature (22-26°C), and response time (10-15s) with pump activation 2-3 times/day, making it the most suitable for efficient and sustainable irrigation management.

**Table 3.5:** Results of Experimental Tests

Variables	Sandy Soil	Clay Soil	Loamy Soil
Soil Moisture (%)	12-22	28-39	21-32
Relative Humidity (%)	52-62	71-80	60-72
Temperature (°C)	26-30	22-25	22-26
Water Flow rate (cl/h)	50-65	32-50	9-12
Response Time (s)	5-10	15-20	10-15
Pump Activation (times/day)	3-4	1-2	2-3

#### 4.0 Discussion

The automated irrigation system developed in this study was assessed through simulations and experimental validation. Its core operation uses soil moisture sensors interfaced with a microcontroller, enabling monitoring and automatic control of water delivery. Irrigation was initiated only when the moisture content fell below a predetermined threshold, conserving water and promoting resource efficiency. This outcome aligns with prior work by Kumar et al. [3], who emphasized the role of sensor-based irrigation in water-scarce agricultural systems, and Makana et al. [2], who demonstrated the effectiveness of similar systems in improving yield while reducing manual labor. In the component test, the ATmega328P microcontroller performed reliably, processing input from the sensors and activating the relay module with minimal delay. The moisture sensors provided consistent readings, corroborated by repeat trials under varying soil conditions. These observations were consistent with earlier research by Soni et al. [11], Sawant et al. [10], and Hammond et al. [12]. Moreover, the continuity test confirmed the integrity of electrical connections throughout the system, with no evidence of signal loss or power disruption, as emphasized by Sawant et al. [10] and Kumar et al. [3].

Functionality testing revealed that the system reliably activated the irrigation pump based on soil moisture readings, validating its suitability for precision irrigation. This behavior reflects the concept of threshold-based control highlighted by Makana et al. [2], Priandana [13], and Hammond et al. [12], where automation enhances irrigation timing and uniformity. When tested across different soil types, notable differences in water retention were observed. Clay soils retained moisture for extended periods, while sandy soils required more frequent irrigation due to higher infiltration rates.

These results supported data from FAO [1] and aligned with studies by Priandana (13) and Soni et al. [11]. The system effectively adapted to varying soil conditions, highlighting its potential in real-world farming and laying the groundwork for future integration with IoT and advanced calibration tools, as suggested by Hammond et al. [12].

#### 5.0 Conclusion

This study successfully developed and tested a microcontroller-based automated irrigation system aimed at enhancing water use efficiency in agriculture. The key conclusions include:

1. **Water Conservation:** By triggering irrigation only when soil moisture was below optimal levels, the system minimized unnecessary water application, aligning with sustainable agricultural practices.
2. **Labor Optimization:** Automation reduced dependence on manual irrigation, allowing time savings and improved farm management efficiency.
3. **Operational Reliability:** Continuous testing over varying conditions demonstrated the system's robustness and suitability for small to medium-scale agricultural use.

Overall, the system offers a viable solution for improving irrigation efficiency, particularly in resource-constrained environments or areas experiencing irregular rainfall patterns.

## 6.0 Recommendations

To further improve the system's functionality and scalability, the following technical enhancements are recommended:

1. **Sensor Network Expansion:** Deploying multiple sensors across larger or heterogeneous fields will allow better spatial representation of soil moisture, as recommended in precision farming practices
2. **Remote Access Capabilities:** Incorporating communication modules (e.g., GSM, Wi-Fi, LoRa) would enable users to remotely monitor and control irrigation activities, improving system flexibility and decision-making.
3. **Adaptive Threshold Mechanism:** Employing simple statistical models or machine learning algorithms can help adjust irrigation thresholds dynamically based on environmental parameters, enhancing irrigation scheduling and efficiency.
4. **Improved Water Delivery:** Integration of low-pressure drip irrigation components can reduce water losses through evaporation and runoff, supporting more precise water application.

These measures, if implemented, would significantly enhance the system's adaptability, sustainability, and potential for large-scale agricultural applications.

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