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A Crop Adaptive Irrigation System for Improving Farm Yield in Rural Communities

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Abstract: Inefficient irrigation is one of the major causes of low crop yield and poverty among rural farmers in developing countries. Existing smart irrigation systems are often complicated, expensive, and require a high level of literacy, hindering their use by rural farmers. Thus, we propose an adaptive irrigation system that is easy to operate and accessible to farmers in rural communities. The proposed system utilizes sensors to monitor soil moisture levels, temperature, and humidity and delivers water to plants only when necessary, increasing efficiency and reducing water waste. An Arduino UNO board is used to analyze the data from sensors to determine the correct amount of water for each crop. A two-level feedback control system activates the water pump, ensuring the moisture level falls within the desired range. The system also has a user-friendly interface, with an SMS feature that allows users to control and monitor the system remotely. The system was tested for three distinct crops: beans, maize, and tomatoes, and its efficacy, efficiency, and sensor accuracy were evaluated. Results indicate that the system conserves water and increases crop yields by delivering the correct amount of water to each crop. The proposed adaptive smart irrigation system can optimize water consumption, reduce waste, and boost yields, resulting in significant energy and water savings for farmers. This research has implications for agriculture in rural communities. It can reduce the burden on farmers by providing an automated irrigation system that requires minimal human intervention. The system can also be controlled remotely, for easy monitoring and modification. Additionally, the system is cost-effective, making it accessible to small-scale farmers with limited resources.

Keywords: Crop Adaptive, Smart Irrigation, SDGs, Arduino Micro-controller

1. INTRODUCTION

The global population is on a steady rise, and the demand for food is also increasing. Agriculture, being a crucial industry, stands as the foundation and backbone of the economy [1]. This sector alone utilizes 85 percent of the Earth's accessible water sources. Given the consistent growth in population and food requirements, this substantial portion of water usage is expected to continue dominating. Consequently, it becomes important to drive advancements within this sector to improve overall outcomes and results [2].

Irrigation involves the artificial application of water to the soil through various techniques and holds vital significance in agriculture, particularly in regions with limited rainfall [3], [4]. Given the increasing population and higher demand for food, the necessity for efficient irrigation systems that can optimize water usage and boost crop yields has become more pronounced. Currently, most farmers worldwide have adopted irrigation systems. However, the irregular timing of landscape irrigation often leads to challenges like over/under-irrigation, which negatively impact crop productivity. In regions with substantial evaporation rates, over-irrigation can stem from inadequate wastewater distribution or management whereas, under-irrigation contributes to soil salinity, leading to detrimental salt accumulation on the soil surface. These issues arise from the limitations of conventional irrigation systems, which cannot assess farm conditions. Hence, they fail to account for plant requirements, resulting in instances of excessive or inadequate watering [5]. Furthermore, conventional irrigation systems struggle to provide efficient irrigation scheduling, thereby giving rise to unnecessary irrigation cycles and water wastage. To address these concerns, this paper proposes a smart irrigation system.

A smart irrigation system is an innovative strategy for increasing agricultural yield while reducing environmental effects [6], i.e. it uses soil moisture data to determine the soil's irrigation requirements. Nonetheless, some smart

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irrigation systems still depend on periodic human intervention to avoid inefficient water use leading to poor crop yield and environmental degradation. Irrigation systems that utilize sensors and machine learning algorithms have been developed to address these challenges [7]. However, many of these systems are complex, expensive, and require a high level of literacy, limiting their use in rural communities [8], [9], [10].

The Sustainable Development Goals (SDGs) of the United Nations comprise numerous goals relevant to smart irrigation systems. For example, smart irrigation systems can help increase food production and crop yields, contributing to zero hunger (SDG 2). It can also assist in water conservation and reduce the risk of water pollution, leading to clean water and sanitation (SDG 6). Furthermore, smart irrigation systems can help to reduce water withdrawals from rivers/lakes, protecting aquatic ecosystems and thereby helping to sustain life below water (SDG 14) [11]. Lastly, smart irrigation systems can help to reduce the amount of water used for irrigation while also protecting ecosystems and biodiversity on Land (SDG 15) [12].

Thus, to promote smart irrigation systems among farmers in rural communities, this research proposes an easy-to-operate adaptive irrigation system for improving crop yield. The system is designed for easy operation with a Short Message Service (SMS) interface, making it accessible to rural farmers with limited literacy. Unlike the existing smart irrigation systems, the proposed system can further adapt to the water needs of various crops.

The remainder of this paper is organized as follows, Section 2 provides a summary of related works while Section 3 discusses the material and methods used. Section 4 presents the system implementation while Section 5 presents the results and discussion. The paper is concluded in Section 6.

2. RELATED WORKS

Smart irrigation systems are becoming increasingly popular, as they help conserve water and increase crop yields. These systems use sensors and controllers to monitor and analyze soil moisture, weather patterns, and plant water use, and then adjust irrigation schedules and water usage accordingly. Smart irrigation systems are classified into two; central control systems and site-specific control systems. Central control systems are commonly used in large commercial farms and municipal parks. Site-specific control systems are designed for small to medium-sized properties like residential lawns and gardens [13].

A smart irrigation system for gardening based on the Internet of Things (IoT) using Arduino is proposed in [14]. The prototyping model was used to create a smart irrigation system for gardening. A prototype is constructed, tested, and tweaked until it yields a satisfying outcome from which the entire system or product may be produced. Similarly, an IoT-enabled smart irrigation system with image processing is proposed in [15]. This system contains solar panels, charge controllers, batteries, Arduinos, Ethernet shields, relays, humidity sensors, and soil moisture sensors. The Raspberry Pi 3, memory card, and USB web camera are used for image processing. The system evaluates pixel value in webcam photos to determine if the plant's leaves are healthy, partially diseased, or sick. Users are then sent emails with photographs defining the state of the plants.

In other studies, a smart irrigation and monitoring system is presented in [16]. The proposed system is a fully automated irrigation system that employs sensors to collect and broadcast raw data on air humidity, temperature, and soil moisture to the user's device. The system uses a machine learning model to predict water requirements, which can help reduce water usage and save money.

A smart drip irrigation system powered by IoT and web-based applications is introduced in [17]. The system includes a web application to facilitate user interaction and control during drip irrigation. Through this application, users can efficiently manage the water supply from the pump for gardening purposes. The system utilizes various sensors to monitor environmental parameters such as humidity, temperature, and soil moisture. Data collected by these sensors is transmitted to a microcontroller, which accurately calculates the water requirements of the plants. Additionally, the system can be accessed and controlled via a web application on an Android mobile phone, providing users with remote visibility and control from any location.

Authors in [18] present a fresh concept of an IoT smart farming system (ISFS) powered by Raspberry Pi. This system offers autonomous monitoring of essential plant parameters such as irrigation, temperature, humidity, soil moisture, and light intensity. Additionally, the study developed a smartphone application that provides users with a user-friendly interface for monitoring plantation-related conditions. Furthermore, the system enables automatic control of the irrigation system by utilizing data obtained from sensors measuring soil moisture, temperature, and sunlight intensity.

Despite the seeming advancements in smart irrigation technology, its use in rural communities is still limited due to the low literacy level of rural farmers, thereby hampering farm yield. Thus, this research aims to overcome this limitation by designing an easy-to-use smart irrigation system for farmers in rural communities. The proposed system is expected to conserve water, reduce waste, and increase crop yield by providing the right amount of water to each crop. This research will also evaluate the efficacy, efficiency, and sensor accuracy of the proposed system, using three distinct crops: beans, maize, and tomatoes.

The findings of this research have significant implications for agriculture in rural communities. The proposed system can reduce the burden on farmers by providing an automated irrigation system that requires minimal human intervention. It can also reduce water and energy consumption, making it cost-effective and sustainable for small-scale farmers with limited resources. Furthermore, the system can be remotely monitored and controlled, making it easier for farmers to manage their crops.

3. MATERIAL AND METHODS

This work employs a two-level feedback control technique [19] as its foundation. The implementation necessitates the utilization of a microprocessor alongside a soil moisture sensor. The microcontroller and the soil moisture sensor actively monitor the moisture content of the soil at regular intervals, with the microcontroller storing this data within a designated register.

For its operation, the system compares the acquired soil moisture data and a predetermined threshold level. The outcome of this comparison is channeled through a comparator, which dictates the valve's status – whether it should be opened or closed. The utilization of this feedback loop presents dual advantages. Primarily, it aligns water flow with actual demand, thereby significantly reducing the risk of wastage or overflow. Secondly, the system operates with minimal human supervision, enhancing its autonomous functionality.

A. System Description

The proposed smart irrigation system integrates a microprocessor and a soil moisture sensor to implement a two-level feedback control mechanism. This system yields several advantages, including user-friendly operation, cost-effective installation, reduced labor and monitoring demands, minimized water consumption, and low energy usage. Key components of the setup include soil moisture sensors, weather sensors, Arduino Uno, solenoid valves, and a water source. The system's operation revolves around the soil moisture data, temperature, humidity, and local weather conditions. This data is used to optimize water allocation and reduce wastage.

The system code collects and uses the sensor data to regulate the solenoid valve. The code initiates by establishing communication with the soil moisture sensor, following which it enters a continuous loop. In this loop, sensor data is continuously acquired and used to update the system's control logic. When the soil moisture level descends below a predefined threshold, the code signals the water pump to initiate irrigation measures, to a threshold value determined by the specific soil and plant types. Furthermore, the system's activities are relayed to the user via SMS notifications facilitated by a GSM module.

B. Hardware Components Overview

Arduino Uno

The Arduino Uno is a widely used microcontroller board designed for hobbyists, students, and professionals to quickly and easily build and prototype electrical projects. It has features such as digital and analog inputs/outputs, a 16 MHz resonator, an ICSP header, and a micro-USB connection. The board is programmed using the free and open-source Arduino software, based on C++, and has a large community of developers that exchange code and resources online [20]. It is used in robotics, automation, and DIY electronics projects due to its low cost, ease of use, and extensive features

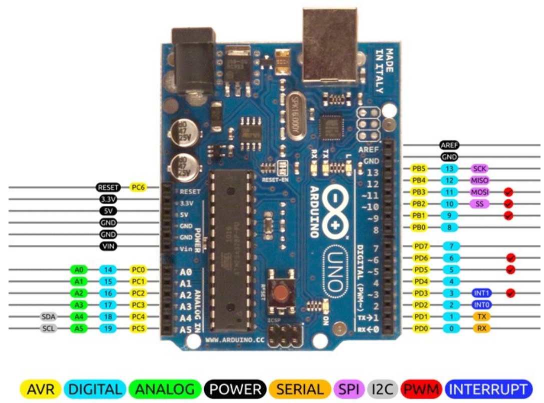

Figure 1. Arduino UNO

Soil Moisture Sensor

Soil moisture sensors are electrical devices that detect water in the soil and are used by farmers, gardeners, and others to monitor soil moisture levels. They work by measuring the electrical conductivity of the soil, which is directly related to the amount of water present. Soil moisture sensors are useful in horticulture, agriculture, landscaping, and environmental monitoring, and provide precise and reliable data for intelligent decisions about watering plants and crops [21].

Humidity Sensor

A humidity sensor or hygrometer is a device that detects moisture levels in the air or gas. They use electrical capacitance, resistance, or thermal conductivity to measure humidity and are used in various applications such as weather monitoring, HVAC systems, and industrial process control. Humidity sensors provide vital data to help regulate environmental conditions and ensure optimal performance in different sectors [22].

GSM Module

A GSM module is a device that allows communication between electronic devices via the GSM network. The SIM900 GSM module is a versatile module for various applications, including remote monitoring and home automation systems. It supports voice, data, SMS, fax communication, TCP/IP, and FTP protocols for Internet connectivity. It has a built-in SIM card slot and supports external antennas for easy network and device connection [23].

DC Water Pump

A DC water pump is a small, portable device powered by a direct current source that can pump water for various applications. It pressurizes and moves water from one location to another, and can be used for irrigation, circulation, and water supply. DC water pumps are efficient, reliable, and can be designed for submersible or surface use.

C. System Architecture

The proposed system operates with a high degree of automation to minimize the need for direct human intervention. This is achieved through an Arduino UNO microcontroller, which controls the system, with a GSM module to facilitate SMS notifications to the user's mobile device. The microcontroller's programming ensures systematic data collection and storage from connected sensors at regular intervals. These sensors measure crucial parameters such as soil moisture, temperature, and humidity level.

After data collection, an analysis is carried out and guided by the plant species, soil composition, and prevailing weather conditions. This analysis ascertains the optimal volume of water required by the plants. Figure 2 shows the block diagram of the proposed system.

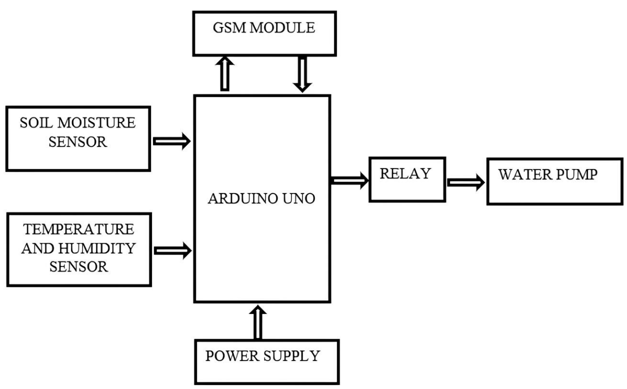

Figure 2. Block Diagram of the System

The Arduino UNO board controls the amount of water delivered to the plants by using actuators, such as a water pump, to open and close the water flow. When the soil moisture level falls below a certain threshold, the micro-controller activates the water pump to irrigate the plants, till the soil moisture level reaches the specified threshold. The appropriate threshold value depends on soil and vegetation type. The board is programmed to activate the actuators based on the data collected by the sensors and the results of the data analysis.

D. System Work Flow

The micro-controller is connected to the GSM module which sends the data collected by the sensors and the current status of the irrigation system to the user as SMS. Figure 3 shows the flowchart of the proposed system. The user will then select the crop type to be irrigated since each plant has a predefined moisture content. The system is programmed to optimize water delivery to plants, reduce waste, and improve crop yields, while also providing real-time data and alerts to users.

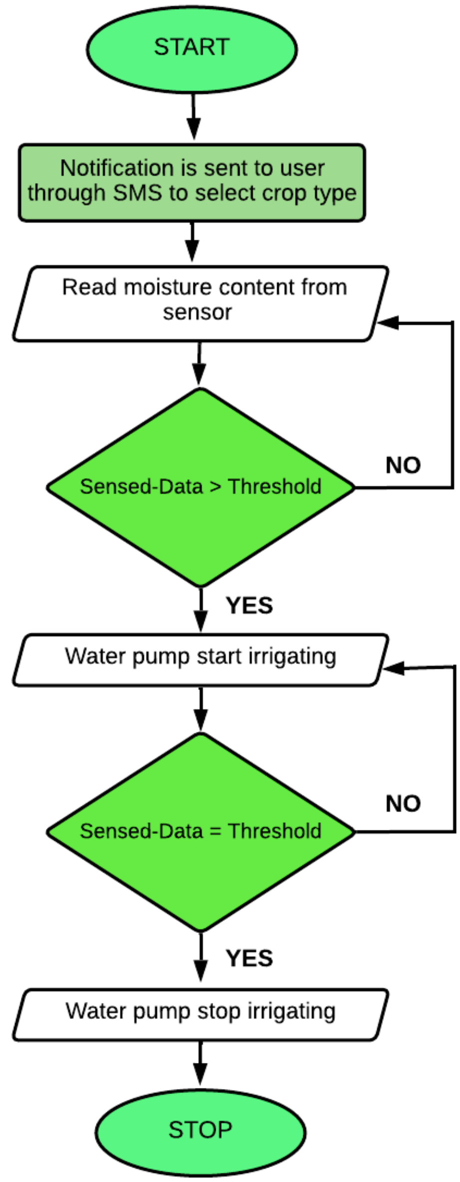

Figure 3. Flowchart of the System

E. Circuit Layout

Figures 4 and 5 present the circuit and schematic diagram of the proposed system.

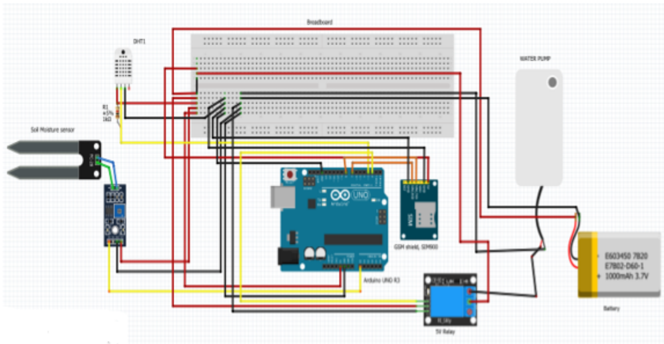

Figure 4. Circuit Diagram of the System

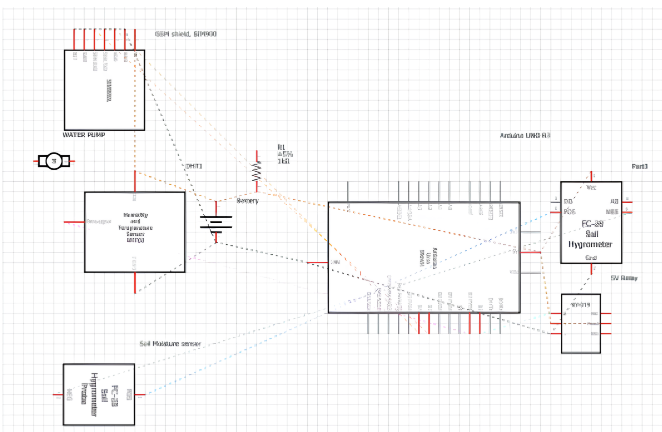

Figure 5. Schematic Diagram of the System

F. Performance Metrics

The metrics used for evaluating the system's effectiveness include water efficiency, energy consumption, and accuracy of sensor readings. Water efficiency measures the amount of water used to maintain healthy plants, whereas, energy consumption refers to the amount of energy consumed to power the various components of the system, The accuracy of sensor readings measures how well the sensor detects and reports the correct value of the physical property being measured.

4. SYSTEM IMPLEMENTATION

Figure 6 shows the system setup. The DHT11 humidity sensor detects temperature and is connected to the microcontroller. The GND pin of the sensor is linked to the Arduino's GND pin, the VCC pin is connected to the 5V pin, and the DATA pin is connected to digital port D3. A 10k resistor is connected to the sensor's DATA and VCC pins to ensure proper communication between the sensor and the Arduino.

For SMS delivery and soil irrigation updates, the SIM900 GSM module is powered using a 5V DC battery. The module configures the RX and TX pins to digital pins D8 and D7 on the Arduino, respectively. A jumper-based toggle mechanism permits the choice of software pins D7 and D8. Activation of the module is orchestrated through the association of the power pin with digital pin D9 on the Arduino. The module's activation is accomplished through a three-second power button press.

The small water pump is controlled by a 5V relay connected to the Arduino. The relay's GND is connected to the Arduino's GND pin, VCC is connected to an external 5V source, and IN is connected to the Arduino's digital pin D2. The relay's output is divided into three sections, NC, NO, and COM. The COM is connected to the positive terminal of the water pump, while either NC or NO can be connected to a 5V supply depending on the coding. The negative terminal of the water pump is connected to the negative terminal of an external 5V supply.

The soil moisture sensor detects moisture in the soil, and if there is moisture, the sensor module and Arduino's A0 pin remain triggered/on, and the relay turns off, which sends an SMS to the user saying ”Pump OFF, Irrigation has ceased,” but the water pump remains on. If there is no moisture, the sensor module turns off, and Pin A0 goes high, causing the relay to turn on, and the water pump to turn on. The Arduino sends an SMS to the user stating ”Pump ON, irrigation has started.” When there is moisture in the soil, the pump turns off automatically.

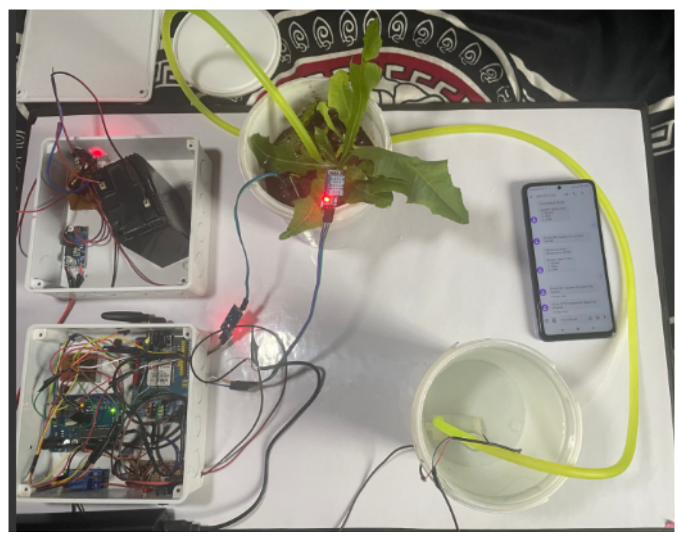

Figure 6. The system setup

A. Software Interface

We utilize the Arduino Integrated Development Environment (IDE) for this paper, which is an application used to develop and upload code to Arduino-based microcontrollers. The code developed through this program serves various purposes. Initially, the inclusion of libraries essential for core functionalities is undertaken. The DHT sensor necessitates the incorporation of DHT.h, the GSM module uses GPRS Shield Arduino.h, while SoftwareSerial.h and wire.h are used for serial monitoring and communication.

Next, some variables are defined, encompassing DHTpin, RX and TX pins, phone number, message content, soil moisture value, and more. Variable data types are also designated for parameters like soilmoistureValue, percentage, temperature, h, and t.

The program initializes the relay and GSM pins to be digitally programmed as HIGH on startup. The DHT sensor is set for operation using the dht.begin function. Through the dht.read method, temperature, humidity, and heat index values are verified, while the Gprs.init function controls the GSM module initialization. The user interaction starts when the user selects a crop type, and this input is captured via the gprs.readSMS function. Based on the user's selection, a switch case mechanism is employed, which directs the execution of the corresponding code segment. Data retrieval from the soil moisture sensor is facilitated by the analogRead function, followed by a transformation into a percentage using the map function.

The code calibrates the soil moisture sensor to obtain the lowest and maximum values necessary to convert them to percentages using the map function. When the selected crop is irrigated, the GSM module sends a message to the user with the defined message for the selected crop, indicating that irrigation has started. If the moisture level exceeds the defined threshold, the relay is digitally written to HIGH (Relay OFF), stopping the water pump. The GSM module then sends a message to the user with the defined message for the selected crop, signaling that watering has ceased. This loop continues until the system is turned off.

5. RESULT AND DISCUSSION

A prototype was designed and tested on three distinct crops to evaluate the effectiveness of the smart irrigation system based on functionality: beans, maize, and tomatoes. The Irrigation scheduling was designed utilizing upper and lower thresholds based on each crop's water needs. The Irrigation procedure for beans was initiated when the soil moisture value reached the lower threshold (5%), and they ceased when the upper threshold was achieved (70%). The Irrigation procedure for maize was initiated when the soil moisture value reached the lower threshold (15%) and discontinued until the upper threshold was achieved (35%). The irrigation procedure for tomatoes was initiated when the soil moisture value reached the lower threshold (7%), and they were terminated when the upper threshold (95%). A summary of three crop types and their predefined threshold is presented in Table 1.

Table 1. Crop Types and their predefined threshold

Crop Types	Lower Threshold (%)	Upper Threshold (%)
Beans	5	70
Maize	15	35
Tomatoes	7	95

Each crop was randomly selected to be irrigated while the system was being tested. When the crop's soil moisture level falls below the predefined lower threshold, the soil moisture sensor sends a signal to the microcontroller, which starts the water pump to irrigate the plants until the soil moisture level rises to the stated level. When the soil moisture level reaches a higher threshold, the soil moisture sensor sends another signal to the Arduino board, and the Arduino board uses the relay to stop the pump. Figure 7 shows the interface displaying the SMS received from the GSM module.

The system optimizes water usage and integrates soil fertility management into the irrigation process. By considering the specific nutrient requirements of each crop type, the system enhances overall crop performance, leading to improved yields and sustainable agricultural practices. This integration of technology and agronomy underscores the potential for our system to revolutionize irrigation practices and contribute to the advancement of modern agriculture.

The system was also tested and evaluated for water efficiency, energy consumption, and sensor accuracy. The water efficiency metric measures the water consumed by the proposed system and compares its water use to that of a conventional irrigation system. This is calculated by dividing the amount of water used by the system by the amount of water needed for the plants. The quantity of water consumed per day is calculated and compared to the amount of water consumed by a typical irrigation system for the same area and crop. This is described in Equation 1.

$$WaterEfficiency = \frac{Amount\ of\ water\ needed}{Amount\ of\ water\ used} \times 100\% \quad (1)$$

Figure 8 compares the water efficiency of the proposed system to a traditional irrigation system; it can be seen the smart irrigation system is more water efficient and assists in conserving more water.

We further assessed the power usage of the smart irrigation system to test its energy consumption. We compare the system's energy use to a typical renewable energy-based irrigation system. We tested with different power-saving settings to observe how they affect energy consumption. Tables 2 and 3 present the power consumed by the two compared devices.

Table 2: Power Consumed by the Renewable Energy-Based Smart Irrigation System

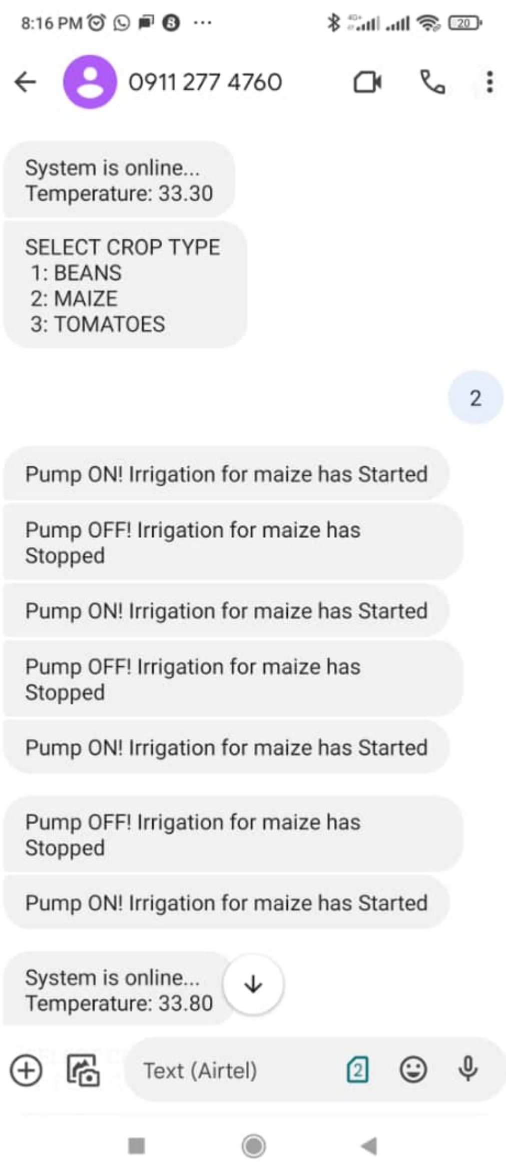

Figure 7. System interface displaying the SMS received from the GSM module

Component Name	Hours Worked (H)	Rating (mA)	Total (mAH)
Arduino 1	12	50	600
Arduino 2	12	50	600
Pump	3 (max time)	1500	4,500
Solenoid	12 (max time)	100	1,200
NodeMCU (Wifi Module)	12	60	720
Total			7.620

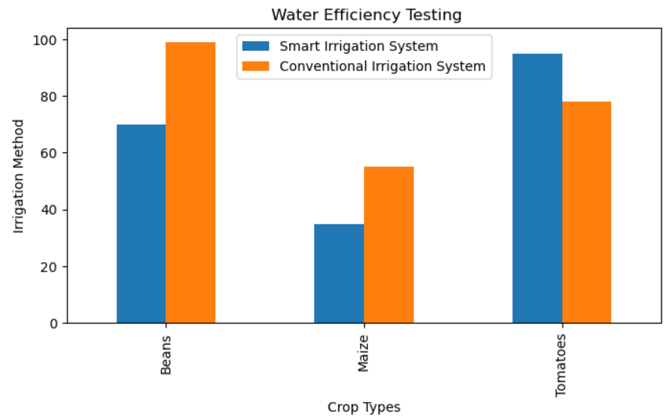

Figure 8. Chart for water efficiency

Table 3: Power consumed by the proposed system

Component Name	Hours Worked (H)	Rating (mA)	Rating (V)	Total (mAH)
Arduino UNO	12	20	12	240
Pump	4	220	5	880
Relay	12	90	5	1,080
GSM Module)	12	150	4.5	1800
Total			26.5	4000

When compared to older smart irrigation systems, the proposed system saves 1,555.1watts. Figure 9 shows the chart for the renewable energy irrigation system versus the proposed system.

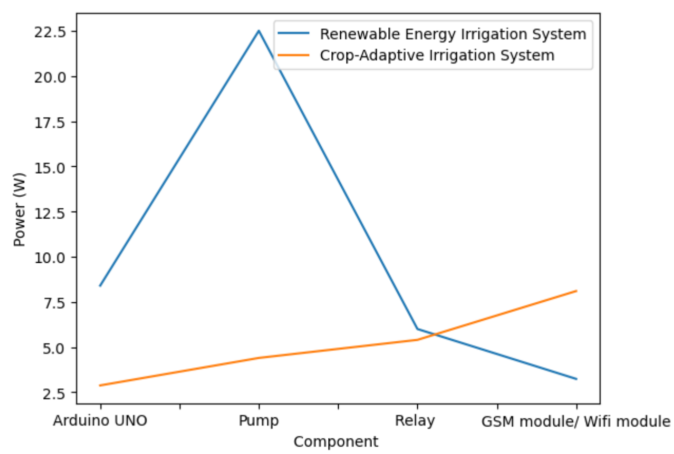

Figure 9. Power consumed by the renewable energy irrigation system versus the proposed system

To determine the accuracy of the sensor reading, we compare the sensor results to real soil moisture levels. We collected soil samples and use a soil moisture sensor to determine the soil's moisture content. The sensor data is then compared to the real soil moisture levels to assess how accurate the sensors are. We also put the sensors through several environmental conditions, such as different soil types, temperatures, and humidity levels. The chart below compares the data acquired from the DHT11 humidity sensor to the temperature of the environment collected from Google Forecast. The difference in these temperatures is not obvious as shown in Figures 10 and 11. As a result, we conclude that the sensor readings are accurate.

Figure 10. Chart for Sensed Temperature versus Realtime Temperature

The chart below compares the value of soil moisture measured with the moisture sensor to the actual moisture value measured with a scale. The moisture was fluctuating at first, but with calibration, the sensor reading became more accurate.

When compared to other works such as [14], [15], [16], this work is simple to operate and can be easily managed by literate and nonliterate farmers. Furthermore, the proposed device can adapt to the irrigation needs of different crops which is a feature lacking in the other works.

6. CONCLUSION

A smart irrigation system is an advanced solution for optimizing irrigation efficiency and conserving water resources. This system utilizes sensors and automation technologies to determine the exact amount of water needed for a specific area, based on factors such as soil moisture levels, weather data, and plant type. This system offers benefits such as accurate and precise water delivery, improved plant growth, time and labor savings, and environmental impact reduction.

This paper focused on addressing the limitations of smart irrigation technology in rural communities due to the low literacy level of farmers. We propose an easy-

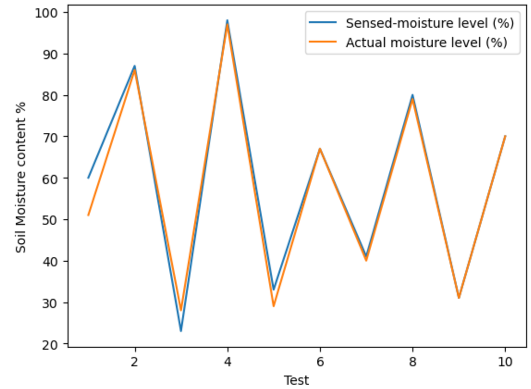

Figure 11. Chart for Sensed-moisture value versus actual moisture value

to-operate smart irrigation system specifically tailored for farmers in rural areas. By designing an intuitive and user-friendly interface, our proposed system ensures that even farmers with low literacy levels can easily operate and control the irrigation process. This promotes accessibility and empowers rural farmers to utilize advanced irrigation technology effectively. The results obtained in this research are encouraging and motivating for further study.

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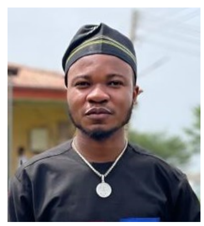

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