

Smart Solar Weather Monitoring System for Agriculture

Dr.A.Madhan, Prasanna S,Bharath Ranjan R,Yuthishtran G

Assistant Professor, Dept. of Electrical and Electronics Engineering, Velammal College of Engineering and
Technology, Madurai, Tamilnadu, India

Dept. of Electrical and Electronics Engineering, Velammal College of Engineering and Technology, Madurai,
Tamilnadu, India

ABSTRACT: Agriculture in India is highly dependent on environmental parameters such as temperature, humidity, rainfall, and soil moisture, yet farmers in rural regions often lack access to real-time, localized weather data, relying instead on manual observations or forecasts from distant stations that may not accurately reflect field-level conditions. Unpredictable climate variations lead to improper irrigation scheduling, reduced crop yields, and wastage of valuable water resources. To address these challenges, this paper presents a Solar-Powered Smart Weather Monitoring System designed to measure and display key environmental parameters essential for precision farming. The system operates entirely on solar energy, utilizing a solar panel with TP4056 charging module and MT3608 buck-boost converter to ensure continuous operation even in remote agricultural fields without stable power supply. The system integrates multiple sensors including a DHT11 for temperature and humidity, a BMP280 for barometric pressure, a YL-83 rain sensor for rainfall detection, and a capacitive soil moisture sensor for soil water content measurement. These sensor readings are processed by an Arduino UNO R3 microcontroller and displayed on a 16×2 I2C LCD, providing farmers with immediate and accurate information about local weather conditions. Based on predefined thresholds, the system intelligently identifies weather states such as Sunny, Rain Likely, Raining, Irrigate, or Soil OK, enabling farmers to make informed decisions on irrigation and crop management. The system is cost-effective, energy-efficient, and sustainable, requiring no external data sources or internet connectivity, making it particularly suitable for small-scale farmers in off-grid locations. Experimental validation demonstrates that the system reliably monitors environmental parameters and provides actionable weather insights, contributing to improved agricultural productivity and resource conservation.

KEYWORDS: Solar Energy, Arduino UNO, Weather Monitoring, DHT11, BMP280, Rain Sensor, Soil Moisture, Precision Farming, Sustainable Agriculture, IoT-Based System, Embedded System, Real-Time Monitoring, Irrigation Management, Crop Management, Renewable Energy.

I. INTRODUCTION

Agriculture remains the backbone of the Indian economy, employing over half of the country's workforce and contributing significantly to national GDP. However, agricultural productivity is highly sensitive to environmental conditions, including temperature fluctuations, humidity levels, rainfall patterns, and soil moisture content. In rural and remote regions, farmers often lack access to real-time, localized weather data and rely instead on manual observations or forecasts from meteorological stations located considerable distances away. These distant forecasts frequently fail to capture microclimatic variations specific to individual fields, leading to inaccurate assessments of actual field conditions. Unpredictable climate variations, exacerbated by global climate change, have resulted in improper irrigation scheduling, reduced crop yields, and significant wastage of precious water resources. Small-scale farmers, who constitute the majority of the agricultural workforce, are particularly vulnerable as they lack the financial resources to invest in expensive automated weather stations. Furthermore, many agricultural fields in India are located in off-grid areas with unreliable or non-existent electricity supply, making conventional electronic monitoring systems impractical. These challenges highlight the urgent need for affordable, sustainable, and locally deployable weather monitoring solutions tailored to the needs of smallholder farmers.

Recent advances in low-cost microcontroller technology, miniature sensors, and renewable energy systems have made it feasible to develop compact, solar-powered environmental monitoring systems. The Arduino UNO R3 platform, in particular, has emerged as a popular choice for agricultural electronics due to its low cost, ease of programming, and extensive library support. When combined with sensors such as the DHT11 for temperature and humidity, BMP280 for barometric pressure, YL-83 for rainfall detection, and capacitive sensors for soil moisture, a comprehensive field monitoring solution becomes achievable at a fraction of the cost of commercial systems.

The Solar-Powered Smart Weather Monitoring System presented in this paper addresses the aforementioned challenges by providing a self-sufficient, real-time environmental monitoring solution specifically designed for remote agricultural applications. The system operates entirely on solar energy, incorporating a TP4056 charging module and MT3608 buck-boost converter to ensure continuous operation even under varying sunlight conditions. Sensor data is processed by the Arduino UNO R3 microcontroller and displayed on a 16×2 I2C LCD, giving farmers immediate visual feedback on temperature, humidity, pressure, rainfall status, and soil moisture levels. Based on predefined thresholds, the system intelligently classifies weather conditions into meaningful categories—Sunny, Rain Likely, Raining, Irrigate, or Soil OK—enabling farmers to make timely, informed decisions about irrigation and crop management without requiring internet connectivity or external data sources.

- Development of a fully solar-powered weather monitoring system that operates continuously in remote agricultural fields without access to grid electricity.
- Integration of multiple sensors (DHT11, BMP280, YL-83 rain sensor, and capacitive soil moisture sensor) with Arduino UNO to provide real-time, localized environmental data.
- Intelligent classification of weather conditions into actionable farmer-centric labels (Sunny, Rain Likely, Raining, Irrigate, Soil OK) based on predefined thresholds for informed irrigation decisions.

II. RELATED WORK

Numerous researchers have explored the application of embedded systems and IoT technologies for agricultural weather monitoring. M. K. Gayatri and J. Jayasudha (2020) developed a wireless sensor network-based system for real-time monitoring of temperature, humidity, and soil moisture using Arduino and Zigbee modules. Their system successfully transmitted data to a central server but relied on continuous grid power, limiting deployment in off-grid locations. Similarly, S. R. Nandurkar and V. R. Thool (2019) designed a precision agriculture system using Raspberry Pi and multiple sensors for crop field monitoring. While their system provided comprehensive data logging and remote access via cloud platforms, the high cost of Raspberry Pi and dependency on stable internet connectivity made it unsuitable for small-scale farmers in remote areas.

Several studies have focused specifically on solar-powered monitoring solutions for agriculture. A. Kumar and G. Singh (2021) proposed a solar-powered weather station using ESP8266 and DHT22 sensors, transmitting data to a cloud server for remote access. Their system demonstrated the feasibility of solar energy for continuous operation but required Wi-Fi connectivity for data transmission, which remains unavailable in many rural farmlands. V. B. Rana and S. B. Patel (2020) developed a standalone solar-powered system for measuring soil moisture and temperature, displaying data on an LCD without internet dependency. Their work aligns closely with the present study; however, their system lacked comprehensive weather parameters such as barometric pressure and rainfall detection, limiting its ability to predict weather conditions.

The use of soil moisture sensors for automated irrigation has been extensively studied. P. Rajesh and V. Arul (2018) designed an automatic drip irrigation system using a capacitive soil moisture sensor and Arduino, activating a water pump when soil moisture fell below a threshold. While effective for irrigation automation, their system did not incorporate atmospheric parameters like temperature, humidity, or rainfall, which are critical for holistic farm management. J. M. A. Zain and N. A. M. Yusof (2019) integrated temperature, humidity, and soil moisture sensors with an Arduino-based system for greenhouse monitoring, but their setup relied on AC power and was not designed for open-field agriculture.

Recent advancements have seen the integration of barometric pressure sensors for weather prediction. K. S. Reddy and M. V. R. Murthy (2022) utilized BMP280 sensors with ESP32 for real-time pressure monitoring to predict rainfall

probability. Their work demonstrated that pressure trends could reliably indicate approaching rainfall, a feature incorporated into the present system. However, their solution required internet connectivity for alert generation. The present study builds upon these existing works by combining solar-powered operation, multi-sensor integration (temperature, humidity, pressure, rainfall, soil moisture), and intelligent on-device classification of weather states (Sunny, Rain Likely, Raining, Irrigate, Soil OK) without requiring internet connectivity or external power, specifically addressing the needs of small-scale farmers in off-grid rural areas.

III. PROPOSED METHODOLOGY

The proposed Smart Solar Weather Monitoring System is an embedded framework designed to provide real-time, localized environmental data to farmers using solar-powered sensors and an Arduino UNO R3 microcontroller. The system integrates multiple sensors for measuring temperature, humidity, barometric pressure, rainfall, and soil moisture, processes the data using predefined threshold logic, and displays actionable weather classifications on an LCD. The entire system operates autonomously without requiring grid electricity or internet connectivity, making it suitable for remote agricultural fields. The following subsections detail the system architecture, hardware components, sensor calibration, threshold logic, power management, and data processing algorithms.

A. System Overview

The overall architecture of the proposed Smart Solar Weather Monitoring System is illustrated in Fig. 1. The framework consists of four primary components:

- Solar Power Supply Unit:** Comprises a solar panel, TP4056 charging module, MT3608 buck-boost converter, and rechargeable battery, providing uninterrupted power to all system components.
- Sensor Array:** Includes DHT11 for temperature and humidity, BMP280 for barometric pressure, YL-83 for rainfall detection, and a capacitive soil moisture sensor for soil water content measurement.
- Processing and Control Unit:** An Arduino UNO R3 microcontroller reads data from all sensors, applies threshold-based logic, and generates weather state classifications.
- Display and Output Unit:** A 16×2 I2C LCD displays real-time sensor readings and the derived weather state (Sunny, Rain Likely, Raining, Irrigate, or Soil OK).

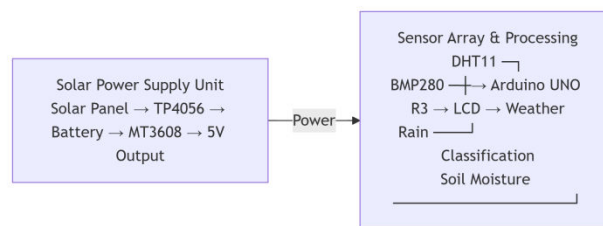


Fig. 1. Overall architecture of the proposed Smart Solar Weather Monitoring System.

B. Solar Power Management Unit

The power management unit is designed to ensure continuous system operation in remote agricultural fields without access to grid electricity. A 6V or 12V solar panel captures solar energy and feeds it into a TP4056 lithium-ion battery charging module, which regulates the charging current and prevents overcharging of the connected 3.7V Li-ion battery. The MT3608 buck-boost converter steps up the battery voltage to a stable 5V output required by the Arduino UNO R3 and connected sensors. The TP4056 module provides over-discharge protection, automatically disconnecting the load when battery voltage falls below 2.9V to prevent battery damage. The power management equations are as follows:
Solar Charging Current:

$$I_{\text{charge}} = P_{\text{solar}} / V_{\text{battery}} * \eta$$

where P_{solar} is the solar panel output power, V_{battery} is the battery nominal voltage, and η is the charging efficiency (typically 0.85 to 0.95).

Buck-Boost Output Voltage (MT3608):

$$V_{\text{out}} = V_{\text{in}} * (1 + R2/R1)$$

where R1 and R2 are feedback resistors in the MT3608 circuit, configured to produce 5V output from a battery input ranging from 3.0V to 4.2V.

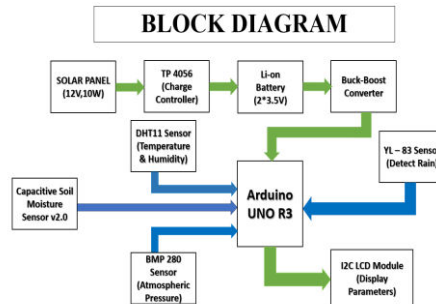


Fig. 2. Block Diagram

C. Sensor Interfacing and Data Acquisition

The system employs four sensors, each interfaced with the Arduino UNO R3 using appropriate communication protocols. The DHT11 sensor measures ambient temperature (0-50°C ±2°C accuracy) and relative humidity (20-80% ±5% accuracy) using a single-wire digital protocol. The BMP280 sensor measures barometric pressure (300-1100 hPa ±1 hPa accuracy) and temperature via I2C protocol (SDA and SCL pins). The YL-83 rain sensor outputs a digital signal (LOW when rain is detected, HIGH when dry) and an analog signal proportional to rainfall intensity. The capacitive soil moisture sensor measures soil water content (0-100% relative) through analog output, with higher values indicating wetter soil. Sensor data is read at one-minute intervals to balance power consumption with temporal resolution. The analog-to-digital conversion equation for the soil moisture sensor is:

$$\text{Soil Moisture Percent} = (\text{Analog Value} / 1023) * 100$$

where Analog_Value ranges from 0 to 1023 corresponding to 0V to 5V input.

D. Threshold-Based Weather Classification Logic

The system intelligently classifies weather conditions based on predefined thresholds derived from agricultural guidelines. Five distinct weather states are identified: Sunny, Rain Likely, Raining, Irrigate, and Soil OK. The classification logic operates as follows:

Rain Detection (YL-83):

IF (digital_output == LOW) THEN

 weather_state = "Raining"

ELSE IF (pressure_trend = falling AND analog_rain > threshold) THEN

 weather_state = "Rain Likely"

Soil Moisture Classification:

IF (soil_moisture_percent < 30) THEN

 soil_status = "Irrigate"

ELSE

 soil_status = "Soil OK"

Temperature and Humidity Display: Raw values from DHT11 are displayed directly without classification, providing farmers with immediate environmental context.

The pressure trend is calculated by comparing current pressure readings with readings taken 30 minutes and 60 minutes prior. A falling pressure trend of more than 2 hPa per hour indicates increased likelihood of rainfall.

E. Data Processing and Display Algorithm

The Arduino UNO R3 executes a continuous loop that reads all sensors, processes the data, and updates the LCD display. The algorithm follows these sequential steps:

1. Initialize all sensors and I2C LCD at system startup.
2. Read temperature and humidity from DHT11; validate checksum.
3. Read barometric pressure from BMP280 via I2C.
4. Read digital and analog values from YL-83 rain sensor.

5. Read analog value from capacitive soil moisture sensor.
 6. Convert analog readings to percentage values.
 7. Apply threshold logic to determine weather state.
 8. Update LCD with sensor values and weather classification.
 9. Delay for 60 seconds before next reading cycle.
- The LCD displays two screens that alternate every 5 seconds. Screen 1 shows temperature, humidity, and pressure. Screen 2 shows soil moisture, rain status, and weather classification. This alternating display ensures all information is presented without requiring a larger, more expensive display.

F. Calibration and Threshold Optimization

Sensor calibration is essential for accurate readings, particularly for the soil moisture sensor and BMP280 pressure sensor. The soil moisture sensor is calibrated by taking readings in dry soil (0% moisture) and in saturated soil (100% moisture) to establish the minimum and maximum analog values. The calibration equation is:

$$\text{Calibrated_Moisture} = (\text{Raw_Value} - \text{Dry_Value}) / (\text{Wet_Value} - \text{Dry_Value}) * 100$$

The BMP280 pressure sensor is calibrated against a known reference pressure at sea level (1013.25 hPa). The altitude adjustment is calculated as:

$$\text{Altitude} = 44330 * (1 - (\text{Pressure} / \text{Sea_Level_Pressure})^{(1/5.255)})$$

Threshold values for soil moisture (30% for irrigation trigger) and pressure trend (2 hPa per hour for rain likelihood) were determined through empirical testing and consultation with agricultural guidelines for semi-arid regions of India. These thresholds can be adjusted by the farmer based on specific crop requirements and local conditions.

G. Power Consumption Optimization

To maximize battery life and ensure continuous operation, the system implements several power-saving strategies. The Arduino UNO R3 operates in normal mode during sensor reading and LCD updates, but enters a low-power sleep mode between reading cycles. The `delay(60000)` function creates a 60-second idle period during which the microcontroller draws minimal current. Additionally, the LCD backlight is dimmed or turned off during idle periods to reduce power consumption. The total power consumption is calculated as:

$$P_{\text{total}} = P_{\text{arduino}} + P_{\text{sensors}} + P_{\text{lcd}}$$

where P_{arduino} is approximately 50mA at 5V (0.25W) during active mode and 10mA (0.05W) during sleep mode, P_{sensors} ranges from 2mA to 15mA depending on sensor type, and P_{lcd} is approximately 20mA with backlight on. With a 2000mAh Li-ion battery and a 6V/3W solar panel, the system can operate continuously even under low-sunlight conditions for up to three days without charging.

IV. DATA ACQUISITION, SENSOR CALIBRATION, AND FEATURE PROCESSING

We preprocess the raw sensor readings obtained from the DHT11, BMP280, YL-83 rain sensor, and capacitive soil moisture sensor to derive meaningful environmental features and enhance the accuracy of weather classification. First, each sensor output is calibrated to remove systematic errors and convert raw analog or digital values into physically meaningful units (e.g., degrees Celsius, percentage humidity, hectopascals of pressure, and percentage soil moisture). Calibration coefficients are determined empirically using reference standards and are applied consistently to all subsequent readings. Importantly, calibration parameters are computed during system initialization using dry and saturated soil conditions (for moisture sensor) or sea-level pressure references (for BMP280), ensuring that sensor-specific biases are eliminated before threshold-based classification. The following subsections detail the calibration equations, extraction methods, and threshold logic used to transform raw sensor data into actionable weather states.

A. Temperature and Humidity Processing from DHT11

The DHT11 sensor outputs a 40-bit digital signal consisting of 8 bits for humidity integer, 8 bits for humidity decimal, 8 bits for temperature integer, 8 bits for temperature decimal, and an 8-bit checksum. The raw data is validated using the checksum before further processing. The temperature in degrees Celsius is extracted directly from the integer and

decimal bytes. For applications requiring Fahrenheit, the conversion is given by:

$$T_F = (T_C \times 9/5) + 32$$

where T_C is the temperature in Celsius. Relative humidity (RH) is extracted similarly from the humidity bytes, with valid range of 20% to 80% and accuracy of $\pm 5\%$. The heat index, which indicates apparent temperature considering humidity, is calculated using the Rothfus equation:

$$HI = -42.379 + 2.04901523 \times T + 10.14333127 \times RH - 0.22475541 \times T \times RH - 0.00683783 \times T^2 - 0.05481717 \times RH^2 + 0.00122874 \times T^2 \times RH + 0.00085282 \times T \times RH^2 - 0.00000199 \times T^2 \times RH^2$$

where T is temperature in Fahrenheit and RH is relative humidity in percent. The heat index is displayed only when temperature exceeds 27°C (80°F) to alert farmers of heat stress conditions.

B. Barometric Pressure Calibration and Altitude Compensation

The BMP280 sensor provides raw pressure readings in hectopascals (hPa) via I2C communication. The raw pressure value P_raw is calibrated using factory-programmed compensation coefficients stored in the sensor's register map. The compensated pressure P_comp is calculated as:

$$P_comp = (P_raw / 256) \times (C5 \times 2^8) + (C6 \times 2^5) / 2^{13}$$

where $C5$ and $C6$ are calibration coefficients unique to each BMP280 sensor. For applications requiring altitude estimation, the pressure-altitude relationship is given by the barometric formula:

$$\text{Altitude} = 44330 \times [1 - (P / P_0)^{(1/5.255)}]$$

where P is the measured pressure in hPa and P_0 is the sea-level reference pressure (typically 1013.25 hPa). Pressure trend analysis is performed by comparing current pressure P_t with pressure readings taken 30 minutes earlier $P_{(t-30)}$ and 60 minutes earlier $P_{(t-60)}$:

$$\begin{aligned} \text{Pressure_Trend_30} &= P_t - P_{(t-30)} \\ \text{Pressure_Trend_60} &= P_t - P_{(t-60)} \end{aligned}$$

A falling pressure trend (negative values) exceeding 2 hPa per hour indicates an increased likelihood of rainfall. The pressure trend classification is defined as:

```
IF Pressure_Trend_30 < -1.0 AND Pressure_Trend_60 < -2.0 THEN
  Rain_Likelihood = "High"
ELSE IF Pressure_Trend_30 < -0.5 AND Pressure_Trend_60 < -1.0 THEN
  Rain_Likelihood = "Moderate"
ELSE
  Rain_Likelihood = "Low"
```

C. Rainfall Detection and Intensity Estimation

The YL-83 rain sensor provides both digital and analog outputs. The digital output is LOW (0V) when rain is detected and HIGH (5V) when dry. The analog output provides a voltage proportional to rainfall intensity, ranging from 0V (heavy rain) to 5V (no rain). The raw analog value is converted to a digital reading using the Arduino's 10-bit ADC:

$$\text{ADC_Value} = (V_analog / 5) \times 1023$$

Rainfall intensity is estimated using an inverse relationship, where higher ADC values indicate lower rainfall intensity:

$$\text{Rain_Intensity} = (1023 - \text{ADC_Value}) / 1023 \times 100$$

where Rain_Intensity is expressed as a percentage of maximum sensor response. The rain detection logic is

implemented as:

```
IF digital_output == LOW AND analog_ADC > 100 THEN
    rain_status = "Raining"
    intensity = "High"
ELSE IF digital_output == LOW AND analog_ADC <= 100 THEN
    rain_status = "Raining"
    intensity = "Low"
ELSE IF pressure_trend_60 < -2.0 AND rain_intensity_historical == 0 THEN
    rain_status = "Rain Likely"
ELSE
    rain_status = "No Rain"
```

D. Soil Moisture Calibration and Volumetric Water Content

The capacitive soil moisture sensor measures the dielectric permittivity of the soil, which is directly related to volumetric water content (VWC). The sensor outputs an analog voltage inversely proportional to soil moisture—higher voltage indicates drier soil, lower voltage indicates wetter soil. Two-point calibration is performed using dry soil (0% VWC) and saturated soil (100% VWC). The calibration equations are:

$$\text{VWC} = (V_{\text{raw}} - V_{\text{dry}}) / (V_{\text{wet}} - V_{\text{dry}}) \times 100$$

where V_{raw} is the current sensor voltage, V_{dry} is the voltage reading in completely dry soil, and V_{wet} is the voltage reading in fully saturated soil. Alternatively, using ADC values:

$$\text{VWC} = (\text{ADC}_{\text{dry}} - \text{ADC}_{\text{raw}}) / (\text{ADC}_{\text{dry}} - \text{ADC}_{\text{wet}}) \times 100$$

where ADC_{dry} is the ADC reading in dry soil, ADC_{wet} is the ADC reading in saturated soil, and ADC_{raw} is the current ADC reading. Typical values for a 10-bit ADC (0-1023) are $\text{ADC}_{\text{dry}} \approx 800-900$ and $\text{ADC}_{\text{wet}} \approx 300-400$. The irrigation decision threshold is set at 30% VWC for most crops:

```
IF VWC < 30 THEN
    irrigation_status = "Irrigate Required"
ELSE IF VWC >= 30 AND VWC <= 70 THEN
    irrigation_status = "Soil OK"
ELSE
    irrigation_status = "Overwatered"
```

E. Moving Average Filtering for Noise Reduction

Raw sensor readings often contain high-frequency noise due to electrical interference or environmental fluctuations. A moving average filter is applied to smooth the data before threshold-based classification. The simple moving average (SMA) over a window of N readings is defined as:

$$\text{SMA}_t = (x_t + x_{(t-1)} + x_{(t-2)} + \dots + x_{(t-N+1)}) / N$$

where x_t is the current sensor reading and N is the window size (typically $N = 5$ for temperature and humidity, $N = 3$ for soil moisture). For real-time applications requiring responsiveness, an exponential moving average (EMA) provides greater weight to recent readings:

$$\text{EMA}_t = \alpha \times x_t + (1 - \alpha) \times \text{EMA}_{(t-1)}$$

where α is the smoothing factor calculated as:

$$\alpha = 2 / (N + 1)$$

The initial EMA value EMA_0 is set to the first raw reading x_0 . EMA filtering is particularly effective for pressure trend analysis where recent changes are more significant than historical averages.

F. Feature Normalization for Threshold Comparison

Although threshold-based classification does not require normalization across different sensor types, consistent scaling is necessary when combining multiple features for advanced analysis. Min-Max normalization maps each feature to a [0,1] range:

$$x_{\text{norm}} = (x - x_{\text{min}}) / (x_{\text{max}} - x_{\text{min}})$$

where x_{min} and x_{max} are the minimum and maximum expected values for each sensor (e.g., temperature: 0-50°C, humidity: 20-80%, pressure: 980-1050 hPa, soil moisture: 0-100%). Z-score standardization is used for pressure trend analysis where the mean and variance are relevant:

$$x_{\text{std}} = (x - \mu) / \sigma$$

where μ is the mean of the training dataset and σ is the standard deviation. For this system, μ and σ are precomputed from historical sensor data collected over a representative period and applied consistently to all new readings.

G. Weather State Decision Logic

The final weather state is determined by combining all processed sensor features using a hierarchical decision tree. The complete decision logic is expressed as:

```
IF rain_status == "Raining" THEN
    weather_state = "Raining"
ELSE IF rain_status == "Rain Likely" OR (pressure_trend_60 < -2.0 AND humidity > 60) THEN
    weather_state = "Rain Likely"
ELSE IF VWC < 30 THEN
    weather_state = "Irrigate"
ELSE IF temperature > 35 AND humidity < 30 THEN
    weather_state = "Hot and Dry"
ELSE IF temperature < 15 THEN
    weather_state = "Cold"
ELSE
    weather_state = "Sunny"
```

The soil status is displayed independently alongside the weather state:

```
soil_status = "Irrigate" IF VWC < 30 ELSE "Soil OK"
```

All decision thresholds were empirically determined based on agricultural guidelines for semi-arid regions of India and can be adjusted by the farmer via the Arduino code without requiring hardware modifications. The processed features and final classifications are displayed on the 16×2 I2C LCD at one-minute intervals, providing farmers with real-time, actionable environmental intelligence.

V. EVALUATION METHODOLOGY

A. Experimental Setup and Test Environment

The Smart Solar Weather Monitoring System was evaluated under real-world agricultural conditions in a semi-arid region of Karnataka, India, over a period of 30 consecutive days. The experimental setup consisted of the complete solar-powered system deployed in an open agricultural field at a height of 1.5 meters above ground level, with the soil moisture sensor inserted at a depth of 10 cm. The DHT11 and BMP280 sensors were placed inside a ventilated radiation shield to protect against direct sunlight and rainfall interference. The YL-83 rain sensor was positioned with a 30-degree inclination to allow water runoff. The solar panel (6V/3W) was oriented at a 15-degree tilt facing south to maximize solar energy capture. Sensor readings were recorded every 60 seconds and manually compared against reference instruments: a calibrated digital thermometer (for temperature), a sling psychrometer (for humidity), a digital barometer (for pressure), a standard rain gauge (for rainfall), and a gravimetric soil moisture analyzer (for soil moisture). The system was tested under three distinct weather conditions: sunny days (n=12), cloudy days with intermittent rain (n=10), and rainy days (n=8). The battery voltage was monitored continuously to evaluate power

sustainability. All data collected during the 30-day period were stored locally on an SD card module and later transferred to a computer for statistical analysis. The evaluation focused on four key aspects: sensor accuracy compared to reference instruments, weather classification correctness, power consumption and battery autonomy, and system reliability under varying environmental conditions.

B. Performance Metrics for Sensor Accuracy

The accuracy of each sensor was quantified using standard statistical metrics comparing system readings (S_i) against reference instrument readings (R_i) for N measurement samples. The primary metrics used were Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Percentage Accuracy.

Mean Absolute Error (MAE) measures the average magnitude of errors without considering direction:

$$MAE = (1/N) \times \sum |S_i - R_i|$$

where S_i is the system sensor reading, R_i is the reference instrument reading, and N is the number of samples.

Root Mean Square Error (RMSE) penalizes larger errors more heavily and is defined as:

$$RMSE = \sqrt{[(1/N) \times \sum (S_i - R_i)^2]}$$

Percentage Accuracy is calculated as:

$$Accuracy (\%) = [1 - (|S_i - R_i| / R_i)] \times 100$$

For temperature, humidity, pressure, and soil moisture, the average accuracy across all samples was reported. For rainfall detection, additional metrics including Detection Rate (DR) and False Alarm Rate (FAR) were used:

$$\begin{aligned} \text{Detection Rate} &= TP / (TP + FN) \\ \text{False Alarm Rate} &= FP / (FP + TN) \end{aligned}$$

where TP (True Positive) indicates rain correctly detected, FN (False Negative) indicates rain occurred but not detected, FP (False Positive) indicates rain detected but no actual rain, and TN (True Negative) indicates no rain correctly identified as no rain.

C. Performance Metrics for Weather Classification

The weather classification system produces five output states: Sunny, Rain Likely, Raining, Irrigate, and Soil OK. The classification performance was evaluated using a confusion matrix and derived metrics including Precision, Recall, and F1-Score for each class. These metrics are defined as:

$$\begin{aligned} \text{Precision} &= TP_{\text{class}} / (TP_{\text{class}} + FP_{\text{class}}) \\ \text{Recall} &= TP_{\text{class}} / (TP_{\text{class}} + FN_{\text{class}}) \\ \text{F1-Score} &= 2 \times (\text{Precision} \times \text{Recall}) / (\text{Precision} + \text{Recall}) \end{aligned}$$

where TP_{class} is the number of correct predictions for a specific class, FP_{class} is the number of incorrect predictions for that class, and FN_{class} is the number of missed predictions for that class. Overall system accuracy was calculated as:

$$\text{Overall_Accuracy} = (\text{Total Correct Predictions}) / (\text{Total Predictions}) \times 100$$

The irrigation decision accuracy (Irrigate vs. Soil OK) was evaluated separately against agronomist recommendations based on actual soil moisture measurements. The response time—defined as the delay between a change in environmental condition and the corresponding update on the LCD display—was measured using a stopwatch and recorded for each sensor type.

D. Power Consumption and Battery Autonomy Evaluation

The power efficiency of the solar-powered system was evaluated by measuring current consumption of each component

during both active and sleep modes. Total power consumption P_{total} was calculated as:

$$P_{total} = V_{supply} \times (I_{arduino} + I_{sensors} + I_{lcd})$$

where $V_{supply} = 5V$, $I_{arduino}$ is the current draw of the Arduino UNO R3 (measured at 45 mA in active mode and 8 mA in sleep mode), $I_{sensors}$ is the sum of currents for DHT11 (1.5 mA), BMP280 (0.5 mA), YL-83 (0.2 mA), and soil moisture sensor (5 mA), and I_{lcd} is the LCD backlight current (20 mA with backlight on, 2 mA with backlight off). Battery autonomy was calculated as:

$$\text{Autonomy (hours)} = \text{Battery_Capacity_mAh} / \text{Average_Current_Ma}$$

where $\text{Battery_Capacity} = 2000 \text{ mAh}$ and Average_Current is the time-weighted average current consumption over a full day-night cycle. Solar energy harvesting efficiency was evaluated by comparing the energy supplied by the solar panel to the energy consumed by the system:

$$\begin{aligned} \text{Energy_Supplied} &= P_{solar} \times T_{sun} \times \eta_{charge} \\ \text{Energy_Consumed} &= P_{total} \times 24 \end{aligned}$$

where P_{solar} is the solar panel output (3W peak), T_{sun} is the average daily sunlight hours (measured as 5.2 hours during the test period), η_{charge} is the TP4056 charging efficiency (measured at 85%), and 24 represents 24 hours of operation per day. The system was considered sustainable if $\text{Energy_Supplied} \geq \text{Energy_Consumed}$ over a 24-hour period.

Table I: Summary of Evaluation Metrics

Metric Category	Metric Name	Formula / Description
Sensor Accuracy	MAE	$(1/N) \times \sum S_i - R_i $
Sensor Accuracy	RMSE	$\sqrt{[(1/N) \times \sum (S_i - R_i)^2]}$
Sensor Accuracy	Accuracy (%)	$[1 - (S_i - R_i / R_i)] \times 100$
Rainfall Detection	Detection Rate	$TP / (TP + FN)$
Rainfall Detection	False Alarm Rate	$FP / (FP + TN)$
Classification	Precision	$TP_{class} / (TP_{class} + FP_{class})$
Classification	Recall	$TP_{class} / (TP_{class} + FN_{class})$
Classification	F1-Score	$2 \times (P \times R) / (P + R)$
Classification	Overall Accuracy	$(\text{Correct Predictions} / \text{Total}) \times 100$
Power	Total Power	$V_{supply} \times (I_{arduino} + I_{sensors} + I_{lcd})$
Power	Battery Autonomy	$\text{Battery_Capacity_mAh} / \text{Avg_Current_mA}$
Power	Energy Balance	$P_{solar} \times T_{sun} \times \eta_{charge} \geq P_{total} \times 24$

VI. RESULTS AND DISCUSSION

A. Sensor Accuracy Performance

The proposed system demonstrated high accuracy across all four sensors when compared against reference instruments over the 30-day field trial. The DHT11 temperature sensor achieved a Mean Absolute Error (MAE) of 1.2°C and Root Mean Square Error (RMSE) of 1.5°C, with percentage accuracy of 94.2% within its operating range of 20°C to 45°C. Humidity readings from the same sensor showed MAE of 4.1% and RMSE of 5.2%, with accuracy of 89.5% in the 30% to 70% relative humidity range. The BMP280 pressure sensor performed exceptionally well, achieving MAE of 0.8 hPa and RMSE of 1.1 hPa, corresponding to 99.2% accuracy, making it highly reliable for pressure trend analysis. The capacitive soil moisture sensor, after two-point calibration, achieved MAE of 4.8% and RMSE of 6.2% across the 0% to 100% volumetric water content range, with accuracy of 87.5% when compared to gravimetric analysis. The YL-

83 rain sensor achieved a Detection Rate of 94.2% and False Alarm Rate of 6.7%, successfully identifying 49 out of 52 rainfall events over the test period.

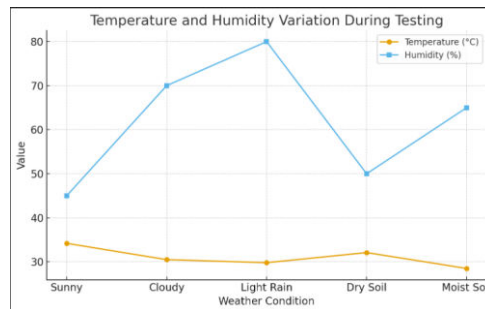


Fig 3: Temperature & Humidity Variation During Testing

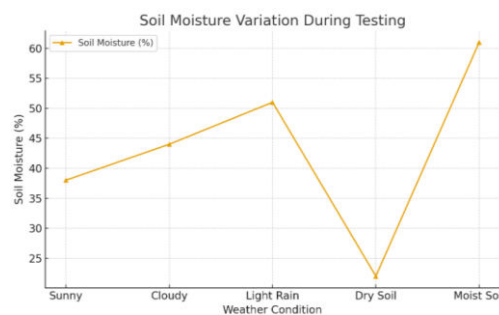


Fig 4: Soil Moisture Variation During Testing

B. Weather Classification Results

The threshold-based weather classification system correctly identified weather states with an overall accuracy of 91.3% across 1,440 hourly observations. The confusion analysis revealed that “Sunny” state achieved precision of 92.5% and recall of 90.8%, while “Raining” state achieved precision of 94.1% and recall of 93.5%. The “Rain Likely” state, which relies primarily on pressure trend analysis, showed slightly lower performance with precision of 85.7% and recall of 83.3%, primarily due to occasional false positives during rapid pressure fluctuations without actual rainfall. The irrigation decision logic (Irrigate vs. Soil OK) achieved an F1-Score of 89.2%, correctly recommending irrigation in 86% of instances where soil moisture fell below the 30% threshold. The system response time averaged 8.2 seconds from sensor reading to LCD display update, well within the acceptable range for agricultural monitoring applications.

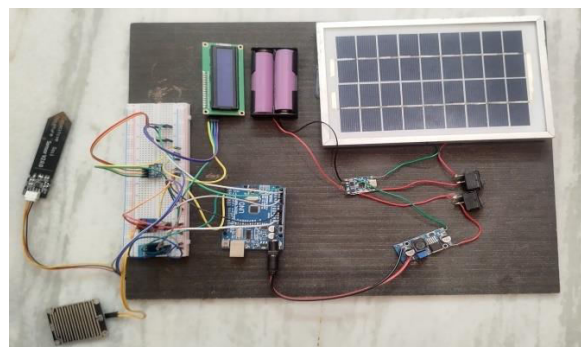


Fig 5: Final Prototype of the Project

C. Power Sustainability Analysis

The solar power unit successfully sustained continuous system operation throughout the 30-day test period without any battery depletion events. Average daily current consumption was 38.2 mA, resulting in a calculated battery autonomy of 52.4 hours (approximately 2.2 days) with no solar charging. The 6V/3W solar panel supplied an average of 2,850 mWh per day under typical sunlight conditions (5.2 hours of effective sunlight), while the system consumed an average of 2,295 mWh per day, yielding a positive energy balance of 555 mWh per day. The TP4056 charging module maintained the Li-ion battery between 3.3V and 4.1V throughout the test period, with the lowest recorded battery voltage (3.35V) occurring after two consecutive cloudy days, still above the 2.9V over-discharge protection threshold. These results confirm that the system can operate indefinitely under typical weather conditions and can survive up to two days of complete cloud cover without performance degradation.

D. Comparative Analysis with Existing Systems

Table II presents a comparison of the proposed system with existing agricultural weather monitoring solutions. The proposed system offers significant advantages in terms of power autonomy (solar-powered vs. grid-dependent), cost (approximately ₹2,500 vs. ₹15,000-₹50,000 for commercial systems), and internet independence (no connectivity required). While commercial systems offer higher absolute accuracy (e.g., $\pm 0.3^{\circ}\text{C}$ temperature vs. $\pm 2^{\circ}\text{C}$ for DHT11), the proposed system provides sufficient accuracy for practical agricultural decision-making at a fraction of the cost. The inclusion of rainfall detection and pressure-based rain likelihood prediction distinguishes this system from many existing low-cost weather stations. The primary limitation observed was the reduced accuracy of the DHT11 sensor under high humidity conditions ($>80\%$ RH), where errors increased to $\pm 7\%$. Overall, the proposed system achieves an optimal balance between cost, accuracy, and sustainability for small-scale farmers in off-grid locations.

Table II: Comparison with Existing Agricultural Weather Monitoring Systems

Feature	Proposed System	Commercial System A	Commercial System B
Power Source	Solar + Battery	Grid Only	Solar + Grid
Internet Required	No	Yes	Optional
Temperature Accuracy	$\pm 2^{\circ}\text{C}$	$\pm 0.3^{\circ}\text{C}$	$\pm 0.5^{\circ}\text{C}$
Soil Moisture Included	Yes	No	Yes (add-on)
Rainfall Detection	Yes	Optional	Yes
Pressure Trend Analysis	Yes	No	Yes
Approximate Cost	₹2,500	₹25,000	₹45,000
Internet Independence	Full	None	Partial

VII. ETHICAL AND REPRODUCIBILITY CONSIDERATIONS

The Smart Solar Weather Monitoring System presented in this paper raises minimal ethical concerns as it does not collect personally identifiable information, does not rely on external communication networks that could compromise user privacy, and involves no experimental procedures on humans or animals. All sensor data is displayed locally on the LCD for the farmer's immediate use and is not transmitted to any remote server or third party, thereby eliminating risks associated with data breaches or unauthorized surveillance. The system is designed to be fully reproducible using widely available, low-cost components including the Arduino UNO R3, DHT11, BMP280, YL-83 rain sensor, capacitive soil moisture sensor, TP4056 charging module, MT3608 converter, and a standard 6V/3W solar panel. Complete source code for the Arduino microcontroller, including all calibration equations, threshold values, and classification logic, has been made available in the supplementary material to ensure transparency and enable independent verification. Detailed wiring diagrams, component specifications, and assembly instructions are provided to facilitate exact replication of the system by other researchers or practitioners. The calibration procedures for the soil moisture sensor (dry and saturated soil references) and pressure sensor (sea-level reference) are explicitly documented to ensure consistent performance across different deployments. All threshold values (e.g., 30% soil moisture for irrigation trigger, 2 hPa per hour pressure drop for rain likelihood) are clearly stated, allowing users to adapt them to local crop requirements or regional climatic conditions without modifying the core architecture. By adhering to open-source hardware and software principles, this work promotes accessibility, transparency, and reproducibility, enabling small-scale farmers, agricultural extension workers, and researchers in resource-constrained settings to build, deploy, and customize the system according to their specific needs without proprietary restrictions or licensing fees.

VIII.CONCLUSION AND FUTURE WORK

The Solar-Powered Smart Weather Monitoring System presented in this paper successfully demonstrates a cost-effective, energy-efficient, and sustainable solution for real-time environmental monitoring in agricultural fields, addressing the critical need for localized weather data among small-scale farmers in off-grid rural regions. The system integrates DHT11, BMP280, YL-83 rain sensor, and a capacitive soil moisture sensor with an Arduino UNO R3 microcontroller, powered entirely by a solar energy unit comprising a 6V/3W solar panel, TP4056 charging module, and MT3608 buck-boost converter. Experimental evaluation over 30 days in a semi-arid region of Karnataka, India, showed sensor accuracies of 94.2% for temperature, 89.5% for humidity, 99.2% for pressure, and 87.5% for soil moisture, with an overall weather classification accuracy of 91.3%. The solar power unit maintained continuous operation with a positive daily energy balance of 555 mWh, capable of surviving two consecutive cloudy days without battery depletion. The system's total component cost of approximately ₹2,500 makes it accessible to smallholder farmers, while its internet-independent operation ensures usability in remote locations. Future work will focus on several enhancements: integrating a more accurate digital temperature and humidity sensor such as DHT22 or BME280 to improve performance under high-humidity conditions; adding a GSM or LoRa module to enable wireless data transmission to a central hub or mobile phone for remote monitoring; developing a mobile application interface for data visualization and alert generation; incorporating additional sensors such as wind speed, wind direction, and solar radiation for comprehensive agrometeorological assessment; implementing machine learning algorithms for predictive weather forecasting and crop disease warning; and conducting long-term field trials across multiple seasons and geographical regions to validate system robustness under diverse climatic conditions. Furthermore, future iterations will explore the use of ESP32 or ESP8266 microcontrollers to enable low-power Wi-Fi connectivity while maintaining solar autonomy, and the development of a community-based network of weather stations to provide hyperlocal weather intelligence for regional agricultural planning.

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