PROJECT REPORT

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Course Title: Embedded System and IoT Lab

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Project Title:

Intelligent Weather & UV Sensing System with Auto-Alert, Roof Control & ThingSpeak Analytics

Abstract

This research presents the design and development of an intelligent and low-cost IoT-based weather and ultraviolet (UV) monitoring system built around the ESP32 microcontroller. The system integrates multiple sensors to measure temperature, humidity, and ultraviolet intensity, processes the collected data to calculate both the Heat Index and UV Index, and then determines a fused risk level to trigger appropriate responses. Based on the assessed conditions, the system activates local safety measures such as a servo-controlled roof mechanism, an RGB LED for visual signaling, and an audible buzzer alarm. For validation and classroom demonstration purposes, a simulation mode is incorporated using potentiometers to mimic sensor data without modifying wiring or hardware. The solution further extends its functionality by uploading telemetry to the cloud through the ThingSpeak platform, allowing remote visualization and long-term data analysis. Robust firmware design ensures reliable data acquisition, safe power practices, and effective separation of sensing, computation, actuation, and cloud upload processes. Overall, the system demonstrates a practical application of embedded IoT technology for enhancing environmental monitoring, personal safety, and smart home or greenhouse automation.

1. Introduction

Extreme heat and high ultraviolet exposure pose significant risks to human health, agricultural productivity, and rooftop structures. With the growing demand for real-time monitoring and preventive safety mechanisms, IoT-enabled solutions are becoming increasingly important. A compact, intelligent, and connected node that can sense environmental conditions, compute associated risks, take protective action, and provide cloud-based reporting is invaluable for both personal and community applications. This project addresses this need by developing an ESP32-based intelligent weather and UV sensing system that demonstrates the full cycle of detection, decision-making, local safety intervention, and cloud analytics. The primary application areas envisioned for this work include residential rooftops, small-scale greenhouses, and occupational safety environments.

2. Objectives

The key objectives of this research were:

- To design a sensing system capable of reliably measuring ambient temperature, humidity, and UV intensity using the DHT11 and an analog UV sensor.
- To compute risk levels by combining Heat Index and UV index values using standard methodologies.
- To actuate visual (RGB LED), audible (buzzer), and mechanical (servo motor) responses based on computed thresholds.
- To develop a simulation environment with potentiometers for controlled testing.
- To upload real-time data to the ThingSpeak cloud for remote monitoring and analysis.
- To ensure robust performance through noise-resistant analog readings, safe power management, and modular firmware design.

3. System Overview

3.1 Functional Blocks

Sensing (Real Mode):
The system collects environmental data using the DHT11 sensor for temperature and humidity, and an analog UV sensor for ultraviolet intensity measurement.

Sensing (Simulation Mode):
Two potentiometers are used as substitutes for real sensors during controlled testing. The POT-TEMP module maps input voltages from 0–3.3 V to a temperature range of 15–45 °C, while the POT-UV module is calibrated to represent UV Index values from 0–11.

Computation:
The ESP32 microcontroller computes the Heat Index using NOAA's polynomial model and maps analog sensor voltages into UVI values. The system then fuses the two parameters, with the overall risk level determined as the maximum of Heat Index and UVI categories.

Actuation:

- **Servo motor (roof control):** Rotates to 180° when UVI ≥ 8, and returns to the previous angle once UVI ≤ 6.
- **Buzzer (thermal alert):** Produces five beeps when the temperature crosses 35 °C, clearing automatically when it drops below 34 °C.
- **RGB LED (visual indication):** Provides intuitive feedback by displaying green, amber, red, and magenta colors corresponding to normal, caution, warning, and danger levels respectively.

Connectivity:
Wi-Fi station mode is employed to transmit sensor readings and computed values to the ThingSpeak cloud platform. Data is mapped to fields 1–8 for remote monitoring and historical analytics.

Debugging and Calibration:
The system outputs serial diagnostic data at a frequency of 1 Hz. In simulation mode, calibration of the UV potentiometer is supported using interactive serial key commands (*z*, *x*, *c*).

3.2 High-Level Block Diagram

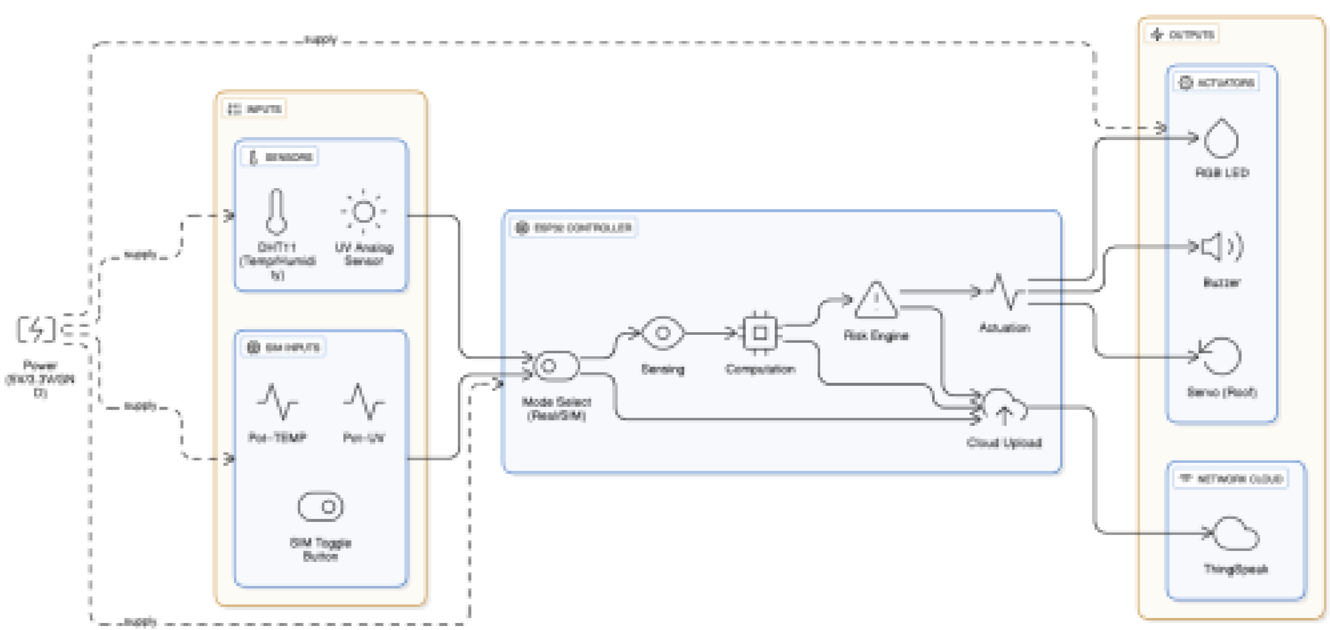

Fig. 1: Overall architecture

4. Hardware Design

4.1 Core Components

- **ESP32 DevKit V1 (ESP32-WROOM-32)**
- **DHT11** (Temp/Humidity)
- **Analog UV Sensor** (OUT/VCC/GND)
- **Two 10 kΩ Potentiometers** (SIM inputs)
- **RGB LED** (common cathode assumed)
- **Buzzer** (active or passive; passive driven by 2.5 kHz tone) with **NPN transistor** driver • **Micro Servo (e.g., SG90)**
- **5 V rail** for servo & buzzer; **3.3 V** for ESP32 & sensors; **common ground**

4.2 Pin & Power Highlights

ADC1 Constraint (UV Sensor on GPIO34):
The analog UV sensor is connected to GPIO34, which belongs to the ADC1 channel of the ESP32. This choice ensures that analog-to-digital conversions can operate simultaneously with Wi-Fi communications, since ADC2 pins become unavailable when Wi-Fi is enabled.

Simulation Potentiometers (GPIO35 and GPIO32):
Two potentiometers are incorporated for simulation mode. The wiper of the UV potentiometer is connected to GPIO35, while the temperature potentiometer wiper is connected to GPIO32. Both are powered between 3.3 V and ground, ensuring safe voltage levels compatible with the ESP32's ADC input range.

Servo Motor Powering (5 V Rail):
The servo motor is supplied from a dedicated 5 V rail. Importantly, the servo must never be powered directly from the ESP32's 3.3 V regulator, as this can cause insufficient current delivery and instability. A common ground is tied between the 5 V rail and the ESP32 to maintain reference consistency.

Buzzer Powering and Protection:
The buzzer is driven via an NPN transistor to ensure sufficient current delivery without overloading the ESP32's GPIO. In cases where a coil-type buzzer is used, a flyback diode is recommended across the terminals to protect against back-electromotive force (EMF).

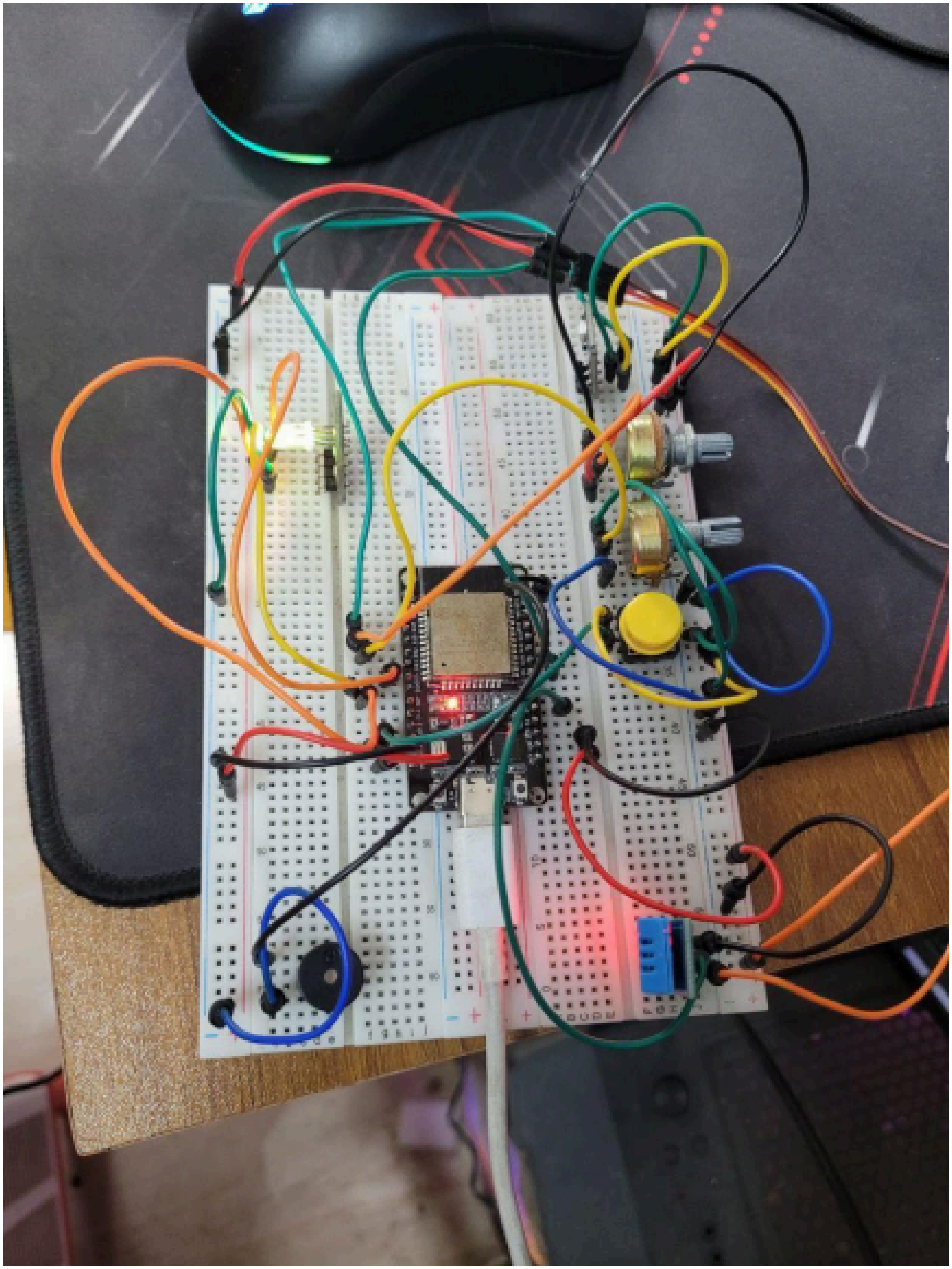

Fig. 2: Real image of the project

5. Software Architecture

5.1 Firmware Layers

Drivers: Utilized the DHTesp library for temperature and humidity sensing, and analog read helpers with exponential moving average (EMA) smoothing and multi-sample averaging for stable UV readings.

Mode & Debounce: Implemented SIM mode toggle on GPIO13 with a 25 ms debounce to ensure reliable switching between real and simulated inputs.

Computation:
Heat Index (HI): Calculated using the NOAA polynomial in Fahrenheit, converted back to Celsius.
Ultraviolet Index (UVI): Derived through linear mapping of sensor voltage (zero ≈ 120 mV, maximum 11 UVI ≈ 2.8 V). Simulation mode allows interactive calibration via serial commands (z, x).

Risk Engine:
UV Risk Levels: 0–2 = Normal, 3–5 = Caution, 6–10 = Warning, ≥11 = Danger.
HI Risk Levels (°C): <32 = Normal, 32–40 = Caution, 41–53 = Warning, ≥54 = Danger.
Overall Risk: Determined by the maximum of the UV and HI categories.

Actuation Policies:
Servo: One-shot rotation to 180° when UVI ≥ 8 (rising) and return when UVI ≤ 6 (falling).
Buzzer: Five-tone burst on temperature upward crossing ≥ 35 °C; alert clears when temperature falls below 34 °C.
RGB LED: Displays real-time risk status with color updates refreshed in each loop cycle.

Connectivity:
Established Wi-Fi connection with retry logic; transmitted sensor data to ThingSpeak every ≥20 seconds. Data fields include: F1 Temperature, F2 Humidity, F3 Heat Index, F4 UVI, F5 UV mV, F6 Risk (0–3), F7 Servo angle, F8 SIM (0/1).

Diagnostics: Provided 1 Hz serial status output for debugging and optional calibration prompts during SIM mode.

5.2 Timing

- **UV read:** ~300 ms
- **DHT cycle:** ~2.5 s
- **Serial status:** 1 Hz
- **ThingSpeak push:** 20 s (≥15 s required by service)

6. Implementation Details

To ensure reliable sensor readings, the system adopted several strategies for noise-resistant analog acquisition. The ADC1 channel was configured with an attenuation level of 11 dB, enabling a wider input voltage range suitable for the UV sensor. Each measurement was based on 16–24 samples, taken with micro-delays between readings to reduce transient noise. An exponential moving average (EMA) filter with a smoothing factor of approximately 0.25 was then applied, which effectively suppressed signal jitter while maintaining responsiveness to rapid environmental changes.

The servo motor was controlled using a one-shot motion approach. This method allowed the system to record the previous angle of the servo and return to it once UV intensity subsided. By employing an attach–move–detach sequence, the servo was activated only during required adjustments, minimizing idle buzzing and conserving power.

Audible alerts were implemented differently depending on the buzzer type. For active buzzers, simple HIGH and LOW logic pulses were sufficient to produce sound. In contrast, passive buzzers required a generated waveform; therefore, an LEDC tone at approximately 2.5 kHz was applied to produce clear and distinct beeps for better audibility.

A simulation mode was incorporated to enhance testing and demonstration capabilities. When enabled, potentiometers substituted for real sensors, providing deterministic input values. The UV potentiometer could be calibrated interactively through serial commands: pressing z mapped the minimum pot position to UVI 0, pressing x mapped the maximum position to UVI 11, and pressing c cleared the calibration, restoring the default linear mapping between 0–3.3 V and UVI 0–11. This flexibility allowed repeatable classroom demonstrations and simplified system validation.

Finally, the system included a robust cloud upload mechanism using the ThingSpeak platform. Data transmission was handled by the HTTPClient library, with only valid values sent to conserve bandwidth and avoid errors. In the event of communication failure, retry logic was activated based on Wi-Fi link status. When failures occurred, the HTTP response code and body were printed via the serial monitor, enabling straightforward debugging and diagnosis.

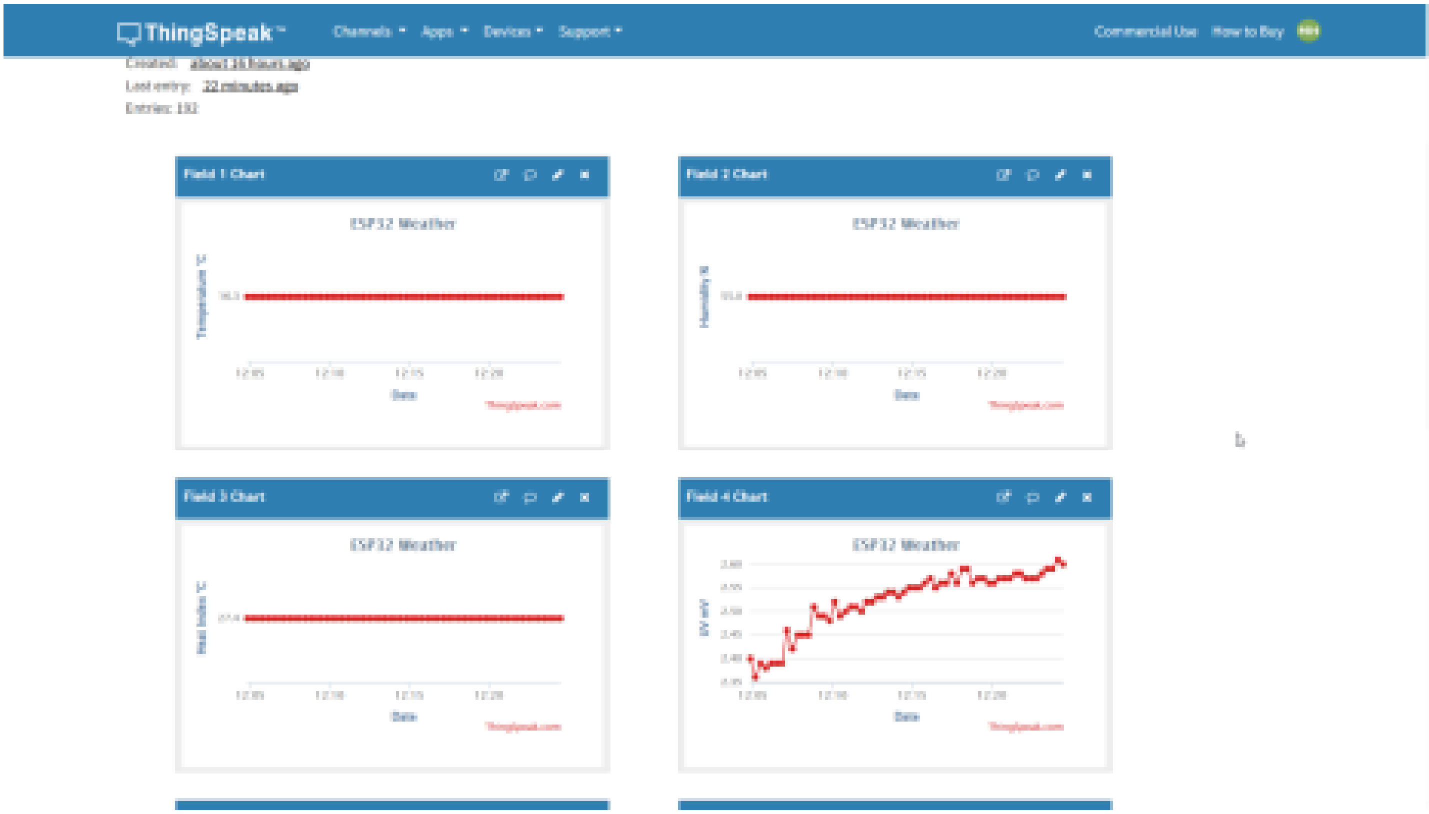

Fig. 3: Monitoring graphs from ThingSpeak

7. Results

Bench Tests

In real mode, the UV sensor recorded stable values below 1 indoors, while the DHT11 consistently measured 30–32 °C and 70–80% RH, matching room conditions. The servo motor responded correctly with hysteresis, moving to 180° only when UVI ≥ 8 and returning at UVI ≤ 6, preventing chatter. The buzzer produced five clear beeps at 35 °C, and ThingSpeak successfully logged data every 20–25 seconds across all fields.

SIM Demonstrations

Simulation mode provided smooth and accurate mapping, with temperature ranging from 15–45 °C and UV calibrated from 0–11. Risk transitions were clearly indicated by the RGB LED, with colors changing consistently according to thresholds.

8. Discussion

The system demonstrated several strengths. Robust ADC1-based analog readings ensured coexistence with Wi-Fi operations, while hysteretic thresholds provided smooth servo behavior. The inclusion of simulation mode not only simplified demonstrations but also enhanced testing efficiency. Cloud integration with ThingSpeak provided analytical capabilities without requiring a local server, making the system scalable for educational and small-scale deployments.

Nevertheless, some limitations were identified. The DHT11 sensor, while low-cost, offers limited accuracy compared to alternatives such as DHT22 or SHT3x. UV intensity mapping was based on linear approximation, which may not fully capture sensor spectral response characteristics. Additionally, powering both the servo and buzzer required careful supply sizing to avoid brownouts and microcontroller resets

9. Testing & Validation Checklist

1. **Continuity & power rails** (5 V and 3.3 V; common GND).
2. **ADC sanity**: pots read 0–3.3 V span, UVI 0–11 after `z/x`.
3. **DHT health**: no TIMEOUT; realistic room values.
4. **Servo**: one-shot to 180° at UVI≥8; return at ≤6.
5. **Buzzer**: five beeps at T≥35 °C rising.
6. **ThingSpeak**: entries ≥20 s with correct fields.
7. **Serial**: minimal 1 Hz lines; SIM toggles reliably.

11. Future Work

Although the system demonstrates reliable performance, several enhancements can be considered for future development. First, replacing the DHT11 with more advanced sensors such as the SHT31 or HTU21 would significantly improve the accuracy of temperature and humidity measurements. Similarly, the use of a digital UV sensor, such as the VEML6075 or ML8511, along with spectral calibration, would provide more precise ultraviolet index readings compared to the current analog module.

From a software perspective, the system could be upgraded to support over-the-air (OTA) firmware updates and captive-portal Wi-Fi configuration, which would simplify maintenance and deployment in new environments. Furthermore, incorporating edge machine learning models could enable intelligent anomaly detection in UV and Heat Index trends, as well as predictive roof actuation based on historical patterns.

In terms of power efficiency, the system could be adapted for off-grid operation by integrating a solar-powered battery supply and implementing deep-sleep scheduling to minimize energy consumption. Such improvements would make the system more suitable for remote applications in agriculture, rooftop safety, and occupational health monitoring in Bangladesh and beyond.

12. Conclusion

This work successfully demonstrates a compact, intelligent, and affordable IoT-based weather and UV monitoring system that integrates sensing, decision-making, local safety measures, and cloud analytics. By balancing robust engineering practices with educational usability features, the system can serve as both a teaching tool and a practical prototype for smart rooftop, greenhouse, and occupational safety applications.

13. References

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