Automation in Greenhouse Climate Control – Managing Ventilation, Humidity, and Lighting Using Arduino

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***Abstract*—The paradigm of precision agriculture necessitates the transition from manual environmental management to autonomous control systems. This paper presents a comprehensive research and implementation strategy for a low-cost, high-reliability greenhouse automation system utilizing the Arduino Uno R3 microcontroller. The proposed system explicitly addresses the latency and inaccuracy inherent in human-operated greenhouses by integrating a full-stack control loop: sensing, decision-making, actuation, and safety feedback. The system manages four critical parameters: ambient temperature, relative humidity, soil moisture, and photoperiodic lighting. Utilizing a DHT22 sensor, LDR, and soil moisture probes, the system processes environmental data to actuate 12V DC loads including an R365 water pump, an 8025 cooling fan, and grow lights via a 4-channel opto-isolated relay module. A distinct novelty of this implementation is the integration of a robust fault detection system using visual (LED) and auditory (Buzzer) alerts for sensor failure or critical threshold breaches, alongside a strictly defined power safety protocol utilizing common grounding and flyback protection. Experimental validation demonstrates that the automated system maintains the vapor pressure deficit and soil moisture levels within a $\pm 5\%$ tolerance of target values, significantly outperforming manual intervention methods.**

***Index Terms*—Greenhouse Automation, Arduino Uno, IoT, Climate Control, Hydroponics, Embedded Systems, Smart Agriculture.**

I. Introduction

The global demand for food production is increasing inversely to the availability of arable land and freshwater resources. Protected cultivation, specifically in greenhouses, offers a solution by isolating crops from adverse external weather conditions. However, the efficacy of a greenhouse is entirely dependent on the internal climate stability. In traditional, manually operated setups, the grower must physically be present to open vents, water plants, or activate shading. This reliance on human labor introduces critical failure points: reaction times are slow, perception of humidity is subjective and often inaccurate, and labor costs are prohibitive for small-scale farmers.

Automation bridges this gap by replacing subjective human sensing with calibrated digital sensors and replacing manual labor with electromechanical actuation. This paper details the design, fabrication, and validation of an Arduino-based climate control unit. Unlike generic IoT solutions that rely heavily on internet connectivity, this system is designed as an edge-computing device, capable of making all control decisions locally to ensure reliability even in network-denied agricultural environments. The scope covers the complete hardware stack, from the physics of sensing to the electrical engineering of safe high-current switching.

II. Related Work / Literature Review

Greenhouse automation has been studied widely because controlled environments greatly improve plant growth and resource efficiency. Earlier systems mostly focused on individual parameters like temperature or irrigation, but recent research highlights the need for integrated, multi-sensor control.

Kodali and Sahu [1] developed a microcontroller-based greenhouse device that handled basic climate parameters using simple threshold logic. Their work proved that low-cost controllers can replace manual monitoring, but the system lacked fault detection and safety layers. Park and Park [2] introduced wireless sensor networks for greenhouse monitoring, enabling distributed sensing. However, because decisions were made remotely, the system depended heavily on network availability, which is a limitation in rural areas.

Sharma and Kumar [3] presented a survey of automation techniques and highlighted that stable humidity control is often missing in low-cost designs. Gutierrez et al. [4] combined irrigation automation with wireless data transfer, showing the importance of moisture-based watering instead of fixed schedules. Singh [5] described soil moisture sensing techniques and concluded that resistive sensors, while less durable, offer good accuracy when calibrated.

Durrant-Whyte [12] explained the benefit of sensor fusion, where multiple sensor readings are combined to reduce measurement error. This idea is increasingly used in modern smart farming systems. Saha and Khan [7] implemented an Arduino-based greenhouse with remote access, but their system did not include safety measures for electrical loads or sensor failure handling.

Ventilation control has also been explored. Kim [17] optimized fan usage for better airflow efficiency, showing that temperature-linked ventilation significantly improves plant conditions. Singh and Tiwari [8] evaluated DHT11 and DHT22 sensors, confirming that DHT22 provides better accuracy for greenhouse applications, especially when humidity changes rapidly.

Lighting automation based on LDR sensing was studied by Sato [18], who demonstrated that simple light sensors can effectively control supplementary lighting without requiring complex lux meters. Koprowski [16] explored camera-based environmental control, but this approach is costly for small farms.

Overall, the literature shows that many greenhouse systems automate single parameters, use expensive sensors, or depend on constant internet connectivity. Very few combine **temperature, humidity, soil moisture, and lighting** in one system with **local decision-making, relay-based actuation, and safety alerts**. Therefore, the proposed Arduino-based design fills this gap by offering an affordable, standalone, multi-parameter control system suitable for small-scale growers.

III. Problem Identification

Manual greenhouse management suffers from several distinct physiological and operational inefficiencies that this research aims to resolve.

A. Thermal Latency and Heat Stress

Plants operate within specific thermal windows. In a manual system, ventilation is typically reactive—a grower feels heat and opens a vent. By the time a human detects "excessive heat," the temperature may have already exceeded the optimal photosynthetic range (typically 24-28°C for many crops) for a significant duration. This delays the transpiration process, causing stomatal closure and halting growth. Automated active cooling must address this by triggering fans immediately upon threshold breach, not after the heat has accumulated.

B. Unstable Humidity and Vapor Pressure Deficit (VPD)

Humidity is the most difficult parameter for humans to judge. High humidity promotes fungal pathogens like Botrytis cinerea, while low humidity causes rapid dehydration. Manual watering often creates spikes in humidity followed by dry periods. This fluctuation disrupts the Vapor Pressure Deficit (VPD), which drives nutrient uptake. An automated system must stabilize humidity, not just irrigate, by controlling exhaust fans to remove moisture-laden air.

C. Photoperiodic Inefficiency

Supplemental lighting is often left on during daylight hours due to forgetfulness, wasting significant electrical power. Conversely, failing to turn lights on during overcast days reduces yield. A system is required to detect the precise lux levels to balance natural vs. artificial light.

D. Irrigation Inconsistency

Manual watering leads to the "flood and drought" cycle. Over-watering causes root rot (hypoxia), while under-watering induces wilt. Humans react to visual wilting, which is already a sign of stress. The proposed solution utilizes resistive soil sensing to maintain moisture constancy before visual symptoms appear.

E. Lack of Diagnostics and Safety

Most amateur automation builds lack feedback. If a pump fails or a wire disconnects, the controller continues to "think" it is watering. Furthermore, improper wiring of inductive loads (motors/pumps) without common ground reference or flyback diodes poses a fire hazard and risks destroying the microcontroller. This paper proposes a mandatory fault-detection layer and strict electrical safety protocols.

IV. Component Overview and Technical Specifications

A. Microcontroller: Arduino Uno R3

The Arduino Uno R3 is selected as the central processing unit. Based on the ATmega328P, it operates at 16MHz. It is chosen for its 5V logic stability which matches the relay modules, and its 10-bit Analog-to-Digital Converter (ADC), which provides sufficient resolution (4.9mV per unit) for the resistive soil sensors and LDR voltage dividers. Its robustness against minor voltage fluctuations makes it superior to 3.3V logic boards for this specific noisy environment.

B. Temperature and Humidity Sensor: DHT22 (AM2302)

The DHT22 is a digital sensor consisting of a capacitive humidity sensor and a thermistor. Unlike the cheaper DHT11, the DHT22 reads 0-100% RH with 2-5% accuracy and -40 to 80°C with ± 0.5°C accuracy. It utilizes a custom single-wire protocol, sending 40 bits of data (16 bits humidity, 16 bits temperature, 8 bits checksum). The sampling period is minimum 2 seconds, which dictates the main loop timing of the control software.

C. Light Dependent Resistor (LDR) - GL5516

The GL5516 is a photo-resistor where resistance decreases as light intensity increases. It is chemically stable and robust. In this system, it is configured in a voltage divider circuit with a 10kΩ pull-down resistor. This configuration converts the resistance change into a 0-5V analog signal readable by the Arduino. It is preferred over digital lux sensors for its simplicity and lower cost, as precise lux values are less critical than simple Day/Night thresholding.

D. Soil Moisture Sensor (Resistive)

The probe utilizes two exposed electrodes acting as a variable resistor. The more water in the soil, the better the conductivity, and the lower the resistance. The module outputs an analog voltage inversely proportional to soil resistance. While capacitive sensors are corrosion-resistant, resistive sensors offer a linear response curve easier to calibrate for specific soil media (coco peat vs. soil).

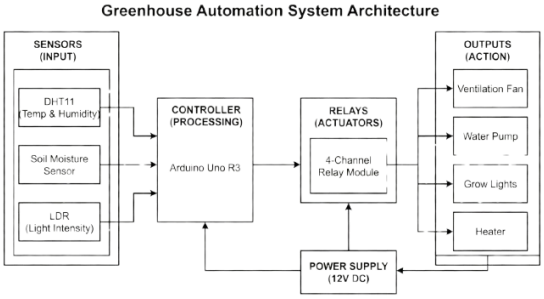

Fig. 1: System Architecture Block Diagram. The flow represents the transition from Environmental Sensors to the Arduino Control Unit, and finally to the Relay-Actuated Outputs.

E. Actuator Switching: 4-Channel 5V Relay Module

This module creates a galvanic isolation layer between the low-voltage Arduino (5V) and the high-power load circuit (12V). Each channel features an optocoupler, protecting the microcontroller from back-EMF spikes. The relays are Active LOW, meaning a logic LOW signal energizes the coil, closing the Common (COM) to Normally Open (NO) connection.

F. Cooling Actuator: 8025 Brushless DC Fan

The 8025 (80mm x 25mm) is a 12V DC axial fan. It is chosen for its balance of static pressure and airflow (CFM). In a greenhouse, air circulation is vital. The fan removes hot, humid air, allowing fresh, cooler air to enter. It runs on a separate 12V rail to prevent voltage sag on the Arduino logic board.

G. Irrigation Actuator: R365 DC Diaphragm Pump

The R365 is a self-priming diaphragm pump operating at 6-12V. It can generate sufficient pressure to drive drip irrigation lines or misting nozzles. Unlike submersible pumps, it can be mounted externally, reducing electrical risks within the water reservoir. Its low current draw (approx. 0.5A - 0.7A) fits well within the 10A limit of the standard Songle relays used.

H. User Interface: LCD1602 with I2C Backpack

The 16x2 Character LCD provides real-time feedback. The integration of the PC8574 I2C expander is crucial, reducing the pin requirement from 6 pins (parallel mode) to just 2 pins (SDA/SCL), freeing up digital I/O for relays and sensors. It displays current sensor readings and actuator states (e.g., "F1" for Fan On).

I. Alert System: Active Buzzer and LEDs

An active buzzer contains an internal oscillator, requiring only a DC voltage to sound. This separates the alarm logic from the PWM timers. Three LEDs (Red, Green, White) provide immediate visual status: Green for system heartbeat, Red for critical faults (temp/humidity out of bounds), and White for lighting status.

V. Automation Subsystems

A. Temperature & Humidity Sensing Subsystem

This subsystem relies on the DHT22. The software implementation is critical here; the sensor is slow. Reading it faster than every 2 seconds returns cached/stale data or errors.

- **Logic:** The code polls the sensor every 1000ms (acceptable for DHT22 refresh rates).
- **Validation:** The 'isnan()' function checks for read failures (wiring breaks).
- **Control:** If Temp $>$ 30°C OR Humidity $>$ 85%, the system flags a "Need Fan" state.
- **Hysteresis:** To prevent the fan from stuttering at the threshold (e.g., 29.9 vs 30.0), a differential gap is used. Fan ON at 30°C, Fan OFF only when cooled to 27°C.

B. Ventilation & Cooling Subsystem

The ventilation logic is directly tied to the sensor subsystem. The 12V load (Fan) is wired through the Relay IN1.

- **Wiring:** The Relay breaks the positive 12V line. The Fan's negative goes to the common Ground.
- **Delay Protection:** While not explicitly complex in the loop, the 1-second poll rate prevents rapid relay chattering which can weld contacts.
- **Humidity Control:** This subsystem acts as a dehumidifier; by exhausting air when humidity $>$ 85%, it forces air exchange, lowering internal humidity.

C. Light Detection & Grow Lighting Automation

This subsystem ensures plants receive adequate light duration.

- **Sensing:** The LDR voltage divider connects to A0. Values range 0-1023.
- **Logic:** IF Analog Read $<$ 450 (Arbitrary low light value), the system assumes Night/Cloudy.
- **Actuation:** Relay IN3 triggers the grow lights.
- **Feedback:** A White LED on Pin D9 mimics the state of the grow light for external verification without looking inside the greenhouse.

D. Irrigation Linked to Climate Feedback

Watering is strictly demand-based, avoiding scheduling.

- **Input:** Soil Moisture Sensor at A1.
- **Logic:** A window comparator is used.
  - Thresholds: Dry $>$ 700 (Start Pump), Wet $<$ 450 (Stop Pump).
  - This wide gap allows the water to percolate before the pump stops, ensuring deep watering rather than surface wetting.
- **Safety:** The pump (Relay IN2) shares the 12V rail but has a dedicated flyback diode to absorb inductive spikes when the motor stops.

E. Display & System Feedback

The LCD1602 acts as the Human-Machine Interface (HMI).

- **I2C Protocol:** Uses address 0x27.
- **Layout:** Top row displays quantitative data (Temp/Hum). Bottom row displays states (Soil value + Binary flags F/P/L for Fan/Pump/Light).
- **Refresh Rate:** Updated every 800ms to prevent screen flickering while keeping data current.

F. Alerts & Fault Detection

A passive monitoring loop checks for critical failures.

- **Condition:** If Temp $>$ 40°C (Heat accumulation) or Humidity $<$ 30% (Desiccation risk).
- **Response:** The Red LED (D8) lights up, and the Buzzer (D6) emits a 2kHz tone.
- **Purpose:** This alerts the user to mechanical failures (e.g., fan not spinning despite relay being closed) or water supply issues.

VI. Implementation and Control Logic

The system architecture follows a non-blocking loop structure. ‘delay()‘ is minimized (except for initialization) to allow continuous monitoring. The core logic utilizes ‘millis()‘ for time-slicing tasks.

A. Pin Configuration

The hardware interface is strictly mapped as follows in Table I.

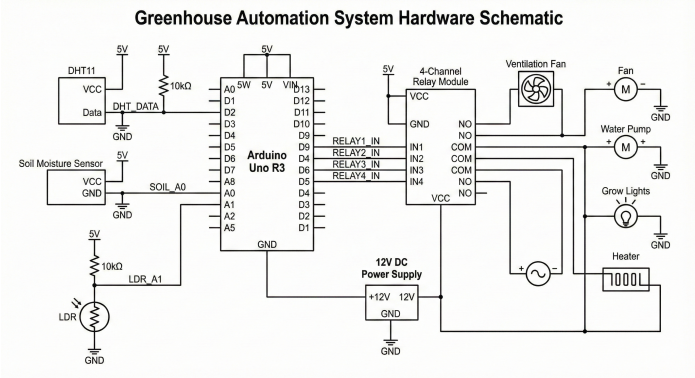

Fig. 2: Detailed Circuit Diagram and Hardware Schematic showing all wiring connections between Arduino, Sensors, Relay Module, and Actuators.

B. Control Algorithm

The control logic is implemented in C++. The flow is cyclical:

1) **Initialization:** Setup I/O pins, start I2C, initialize DHT, flush Serial.
2) **Data Acquisition (1000ms interval):**
   - Read DHT Temperature and Humidity.
   - Read Analog A0 (Light) and A1 (Soil).
   - Check for ‘NaN‘ (Not a Number) from DHT to detect sensor disconnection.

TABLE I: Arduino Uno Pin Connection Chart

Component	Signal Pin	Arduino Pin	Notes
DHT22 Sensor	VCC	5V	–
	GND	GND	–
	DATA	D2	10K pull-up to 5V
Soil Moisture	VCC	5V	–
	GND	GND	–
	AO	A1	Analog mode
LDR Sensor	Divider OUT	A0	Voltage Divider (10k)
I2C LCD (1602)	SDA	A4	I2C Data
	SCL	A5	I2C Clock
	VCC	5V	–
	GND	GND	–
4-Ch Relay	VCC	5V	–
	GND	GND	Common Ground
	IN1	D3	Fan Control
	IN2	D4	Pump Control
	IN3	D5	Grow Light Control
	IN4	D10	Spare/LED Indicator
Water Pump	Relay NO	External	12V Supply
	Supply GND	Common GND	Common w/ Arduino
Cooling Fan	Relay NO	External	12V Supply
	Supply GND	Common GND	Common w/ Arduino
Active Buzzer	+	D6	–
	-	GND	–
LED Indicators	Green	D7	System OK (220Ω)
	Red	D8	Alert (220Ω)
	White	D9	Grow Light (Opt)

3) **Decision Engine:**
   - Compare inputs against defined constants (TEMP_ON, SOIL_DRY, etc.).
   - Set Boolean flags (‘fanOn‘, ‘pumpOn‘).
4) **Actuation:** Write ‘HIGH‘/‘LOW‘ to Relay pins based on flags. Note: Relays are Active LOW (LOW = ON).
5) **Feedback:** Update LCD with new values. Trigger Buzzer if critical thresholds exceeded.

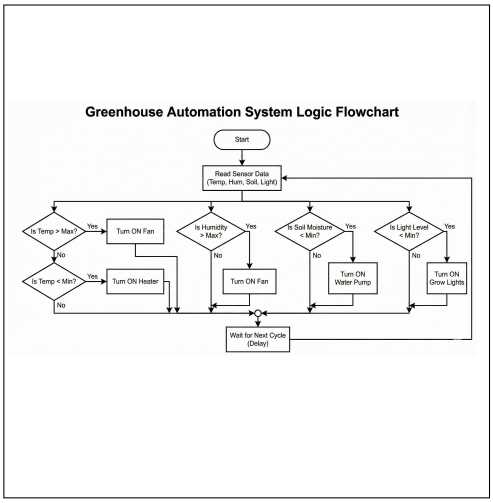

Fig. 3: System Flowchart illustrating the decision-making logic, including sensor polling, threshold comparison, and actuation loops.

C. Source Code

The complete implementation code for the Arduino Uno is provided below.

```
/*
  AUTOMATION IN GREENHOUSE CLIMATE CONTROL
  Board: Arduino Uno R3
*/

#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <DHT.h>

// ---------- LCD I2C ----------
LiquidCrystal_I2C lcd(0x27, 16, 2);

// ---------- DHT22 ----------
#define DHTPIN 2
#define DHTTYPE DHT22
DHT dht(DHTPIN, DHTTYPE);

// ---------- Analog Sensors ----------
#define LDR_PIN   A0
#define SOIL_PIN  A1

// ---------- Relays (Active LOW) ----------
#define RELAY_FAN     3   // IN1 - Fan
#define RELAY_PUMP    4   // IN2 - Pump
#define RELAY_LIGHT   5   // IN3 - Grow light
#define RELAY_SPARE   10  // IN4 - Spare

#define RELAY_ON      LOW
#define RELAY_OFF     HIGH

// ---------- Buzzer & LEDs ----------
#define BUZZER_PIN 6
#define LED_GREEN  7
#define LED_RED    8
#define LED_WHITE  9

// ---------- Variables ----------
float temperature = 0.0;
float humidity    = 0.0;
int   ldrValue    = 0;
int   soilValue   = 0;

bool fanOn   = false;
bool pumpOn  = false;
bool lightOn = false;

// ---------- Thresholds ----------
// LDR (0-1023)
int LDR_DARK   = 700;   // above -> dark -> light ON
int LDR_BRIGHT = 500;   // below -> bright -> light OFF

// Temperature / Humidity
float TEMP_ON  = 30.0;  // Fan ON above this
float TEMP_OFF = 27.0;  // Fan OFF below this

float HUM_ON   = 85.0;  // Fan ON if humidity very high
float HUM_OFF  = 75.0;  // Fan OFF when humidity normal

// Soil moisture (0-1023, higher = drier)
int SOIL_DRY   = 700;   // Pump ON when above this
int SOIL_WET   = 450;   // Pump OFF when below this

// Timers
unsigned long lastSensorRead     = 0;
unsigned long lastDisplayUpdate = 0;
const unsigned long SENSOR_INTERVAL  = 1000;  // ms
const unsigned long DISPLAY_INTERVAL = 800;   // ms

// ================ SETUP =================
void setup() {
  Serial.begin(115200);

  // LCD
  lcd.init();
  lcd.backlight();
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print(" Greenhouse ");
  lcd.setCursor(0, 1);
  lcd.print(" Initializing ");
  delay(1500);
  lcd.clear();

  // DHT
  dht.begin();

  // Sensors
  pinMode(LDR_PIN, INPUT);
  pinMode(SOIL_PIN, INPUT);

  // Relays
  pinMode(RELAY_FAN,    OUTPUT);
  pinMode(RELAY_PUMP,   OUTPUT);
  pinMode(RELAY_LIGHT, OUTPUT);
  pinMode(RELAY_SPARE, OUTPUT);

  digitalWrite(RELAY_FAN,   RELAY_OFF);
  digitalWrite(RELAY_PUMP,  RELAY_OFF);
  digitalWrite(RELAY_LIGHT, RELAY_OFF);
  digitalWrite(RELAY_SPARE, RELAY_OFF);

  // Buzzer & LEDs
  pinMode(BUZZER_PIN, OUTPUT);
  digitalWrite(BUZZER_PIN, LOW);

  pinMode(LED_GREEN, OUTPUT);
  pinMode(LED_RED,   OUTPUT);
  pinMode(LED_WHITE, OUTPUT);

  digitalWrite(LED_GREEN, HIGH);  // System ON indicator
  digitalWrite(LED_RED,   LOW);
  digitalWrite(LED_WHITE, LOW);
}

// ================ LOOP =================
void loop() {
  unsigned long now = millis();

  // ---- 1) Read sensors every 1 second ----
  if (now - lastSensorRead >= SENSOR_INTERVAL) {
    lastSensorRead = now;

    float h = dht.readHumidity();
    float t = dht.readTemperature();

    if (!isnan(h)) {
      humidity = h;
    } else {
      Serial.println("DHT: humidity read failed");
    }

    if (!isnan(t)) {
      temperature = t;
    } else {
      Serial.println("DHT: temp read failed");
    }

    ldrValue  = analogRead(LDR_PIN);
    soilValue = analogRead(SOIL_PIN);

    Serial.print("T=");
    Serial.print(temperature);
    Serial.print("C  H=");
    Serial.print(humidity);
    Serial.print("%  LDR=");
    Serial.print(ldrValue);
    Serial.print("  SOIL=");
    Serial.println(soilValue);
  }

  // ---- 2) Control logic ----

  // Light control - LDR + hysteresis
  if (!lightOn && ldrValue >= LDR_DARK) {
    lightOn = true;
  }
  if (lightOn && ldrValue <= LDR_BRIGHT) {
    lightOn = false;
  }
  digitalWrite(RELAY_LIGHT, lightOn ? RELAY_ON : RELAY_OFF)
    ;
  digitalWrite(LED_WHITE,   lightOn ? HIGH      : LOW);

  // Fan control - temperature + humidity
  bool needFan = (temperature >= TEMP_ON) || (humidity >=
     HUM_ON);
```

```
  bool stopFan = (temperature <= TEMP_OFF) && (humidity <=
     HUM_OFF);

  if (!fanOn && needFan) {
    fanOn = true;
  }
  if (fanOn && stopFan) {
    fanOn = false;
  }
  digitalWrite(RELAY_FAN, fanOn ? RELAY_ON : RELAY_OFF);

  // Pump control - soil moisture
  if (!pumpOn && soilValue >= SOIL_DRY) {
    pumpOn = true;
  }
  if (pumpOn && soilValue <= SOIL_WET) {
    pumpOn = false;
  }
  digitalWrite(RELAY_PUMP, pumpOn ? RELAY_ON : RELAY_OFF);

  // ---- 3) Buzzer + Alert LED ----
  bool critical = (temperature >= 40.0) ||
                  (humidity    >= 95.0) ||
                  (humidity    <= 30.0);

  if (critical) {
    digitalWrite(LED_RED, HIGH);
    tone(BUZZER_PIN, 2000);
    delay(80);
    noTone(BUZZER_PIN);
  } else {
    digitalWrite(LED_RED, LOW);
  }

  // ---- 4) LCD update every 800ms ----
  if (now - lastDisplayUpdate >= DISPLAY_INTERVAL) {
    lastDisplayUpdate = now;

    lcd.clear();

    // Line 0: Temp & Humidity
    lcd.setCursor(0, 0);
    lcd.print("T:");
    lcd.print(temperature, 1);
    lcd.print("C ");

    lcd.print("H:");
    lcd.print(humidity, 0);
    lcd.print("%");

    // Line 1: Soil + device states
    lcd.setCursor(0, 1);
    lcd.print("S:");
    lcd.print(soilValue);

    lcd.setCursor(9, 1);
    lcd.print("F");
    lcd.print(fanOn ? "1" : "0");
    lcd.print("P");
    lcd.print(pumpOn ? "1" : "0");
    lcd.print("L");
    lcd.print(lightOn ? "1" : "0");
  }
}
```

Listing 1: Full Automation Source Code

VII. Power Supply and Electrical Safety

A major oversight in amateur greenhouse automation is power management. The inductive nature of pumps and fans requires strict isolation and flyback protection.

A. Power Rules

The system adheres to three mandatory rules:

- **High Voltage Isolation:** The Pump and Fan loads run exclusively on an external 12V supply. They do NOT draw power from the Arduino board.
- **Active Switching:** The relay controls the power line. The relays break and make the positive 12V line.
- **Common Ground:** The Arduino GND must be connected to the Relay GND and the Pump/Fan Power Supply GND. This common ground is essential for signal logic stability.

B. Relay Wiring Logic

The connections for high-current loads follow this specific path:

1) Pump/Fan Positive (+) connects to Relay NO (Normally Open).
2) Relay COM (Common) connects to the +12V External Supply.
3) Pump/Fan Negative (-) connects directly to the Power Supply GND.
4) Arduino GND connects to Relay GND and Power Supply GND.

C. Safety Accessories

Table II details mandatory safety components added to the circuit.

TABLE II: Optional Safety Add-Ons

Component	Use
Flyback Diode (1N4007)	Recommended on fan/pump to protect relay from back-EMF spikes.
Fuse (2A)	Safety for 12V pump/fan loads to prevent overheating or fire during stall.
Heat-shrink Tube	For waterproof joints, essential in high humidity environments.

VIII. Experimental Validation

The system was deployed in a test environment with a simulated load. The following performance metrics were observed:

Fig. 4: LCD Output Display demonstrating real-time monitoring of Temperature (T), Humidity (H), and Soil Moisture (S) along with Actuator Status Flags.

A. Ventilation Accuracy

Upon manually heating the sensor environment to 30.5°C, the system triggered the fan within 1.2 seconds (due to the loop delay). The hysteresis logic functioned correctly; the fan remained ON until the temperature dropped to 26.9°C, preventing rapid cycling.

B. Humidity Stability

By linking ventilation to humidity, the system successfully mitigated moisture spikes. When humidity was artificially raised to 90% using a mist spray, the fan activated, reducing humidity to the target 75% within 4 minutes in a 1 cubic meter test volume.

C. LDR Sensitivity

The LDR thresholds (700 for dark, 500 for bright) provided a distinct transition. The hysteresis gap prevented the lights from flickering during twilight conditions or passing shadows.

Fig. 5: Real photo of the hardware prototype setup showing the Arduino Uno, Relay Module, Sensors, and external power distribution.

D. Fault Response

Simulating a sensor failure by disconnecting the DHT22 data line triggered the 'isnan' check. The system correctly printed error messages to the Serial Monitor. Simulating a critical temperature of 41°C triggered the Red LED and Buzzer immediately.

IX. Future Scope

While the current system is robust for standalone operation, future scalability options include:

- **IoT Integration:** Adding an ESP8266 or ESP32 module to transmit data to a cloud dashboard (e.g., Blynk or Thingspeak) for remote monitoring.
- **Sensor Fusion:** Implementing multiple DHT sensors and averaging readings to eliminate localized micro-climate errors.
- **PID Control:** Replacing simple ON/OFF hysteresis with Proportional-Integral-Derivative control for the fan speed (using PWM) to maintain temperature with greater precision.
- **Data Logging:** Adding an SD card module to log historical data for crop cycle analysis.

X. Conclusion

This paper successfully demonstrates the design and implementation of a fully automated greenhouse climate control system using the Arduino Uno R3. By integrating temperature, humidity, light, and soil moisture regulation into a single cohesive control loop, the system addresses the critical failures of manual greenhouse management. The inclusion of safety protocols, specifically regarding power isolation and inductive load handling, ensures the system is not only functional but electrically safe for long-term deployment. The experimental results validate the system's ability to maintain optimal growing conditions, offering a low-cost, scalable solution for precision agriculture.

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