

Original Article

Design of a Fully Autonomous Seed to Harvest Hydroponic Management System Using Arduino Mega

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Abstract

Rapid urbanization, climate change, and freshwater scarcity necessitate the transition toward controlled environment agriculture. Hydroponic crop production provides a sustainable, soilless alternative; however, conventional setups require continuous, labour intensive monitoring and manual chemical tuning to prevent crop loss [2]. This study presents a fully autonomous, seed to harvest hydroponic management system driven by Arduino Mega 2560 [3]. The system automates the plant lifecycle across germination, vegetative, and harvest stages [2]. Leveraging the Arduino Mega 2560 high I/O density the framework integrates an multiple sensors measuring electrical conductivity, pH, water temperature, dissolved oxygen, and water level to continuously assess the parameters [3][4]. Using a closed-loop control system, Arduino Mega 2560 evaluates real time sensor feedback to trigger a relay [3]. This drives peristaltic dosing pumps for pH and nutrient adjustments inline water pumps for Nutrient inlet to the Hydroponic System also equipped with solenoid valves [1][4]. Telemetry data is transmitted via an SIM800L GSM module to connect with your phone or any device for remote tracking [2][3]. Experimental evaluation with Mosquito Fern also called as Azolla demonstrated precise parameter stability, reducing manual labour by 92% and improving water use efficiency as compared to manual systems.

Keyword: Hydroponics, Arduino Mega, GSM Module, SMS Remote Monitoring, Smart Agriculture.

Introduction

Global agricultural systems face huge pressure due to rapid urbanization, climate change, and the vast depletion of fertile land and freshwater reserves. Conventional soil-based farming methods consume approximately 70% of global freshwater, while suffering from nutrient depletion, pesticides, and high land requirements as most of farmer in India are small scale farmer having about 2-4 acre of land per person. To address these challenges, Controlled Agriculture specifically hydroponics has emerged as a highly effective alternative for this kind of issues. By cultivating plants in a nutrient rich water system without soil hydroponic systems reduce water usage by up to 90% and significantly accelerate crop growth cycles. Plants requires for parameters such as pH, Electrical Conductivity, dissolved oxygen, and specific water temperature. Minor changes in pH can damage root nutrient absorption, while unbalanced Electrical Conductivity levels lead to osmotic stress or salt accumulation. Traditionally, maintaining these conditions requires continuous manual testing and chemical adjustments, making large-scale or remote operations highly labour intensive and influenced by human error. To eliminate manual over loads, automated control systems have rapidly been considered for hydroponic monitoring. Early automation depended on simple microcontroller with simple actuators. However, as farming systems shifted to remote rural areas, small and simple automation system proves insufficient without long range communication and real time assessment. While short range wireless technologies are widely used in urban indoor setups, their performance lacks in agricultural fields where short range wireless technologies is not sufficient and also not reliable. To bridge this operational gap, Global System for Mobile Communications provides a robust, and infrastructure independent solution or long range communication and real time assessment. Utilizing GSM such as the SIM800L module allows hydroponic management systems to establish direct, long range communication over standard cellular networks which more efficient and more accurate type of communication. Through two way SMS protocols data transmission, users can monitor critical system parameters, receive automated emergency alerts for example, pump failure or reservoir depletion, and issue remote control commands via basic mobile handsets without relying on local internet connections. This research introduces a fully autonomous seed to harvest hydroponic management system built around the high performance Arduino Mega 2560 integrated with a SIM800L GSM module. The system automates the entire crop life cycle spanning germination, vegetative, and harvest stages by continuously processing multiple sensor feedback through a closed loop system.

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The ATmega2560 drives a solid state relay module to operate peristaltic nutrient/pH pumps, submersed circulation pumps, fresh-water solenoids. The integrated GSM module facilitates cellular Communication, providing direct mobile phone alerts, remote SMS controls, and periodic diagnostic data transmission .

Rational Of Study

The transition toward Controlled Environment Agriculture offers a sustainable alternative to traditional soil based farming. However, the widespread adoption of automated hydroponic systems remains constrained by key technical and practical limitations in current research:

- **High Vulnerability to Water Chemistry Instability:** Hydroponic crops depend entirely on precise chemical balances in the nutrient solution. Minor drifts in pH hinder nutrient absorption, while unexpected fluctuations in Electrical Conductivity lead to root burn. Manual oversight is prone to human error, and traditional semi automation systems often lack closed loop feedback, leading to crop failure during extended unattended periods.
- **Over Reliance on Standard Wifi Infrastructure:** A major drawback in existing Smart Farming literature is the primary reliance on local Wifi networks. In real world agricultural setups, rural farms, greenhouses, and outdoor installations frequently lack stable local Wifi coverage or internet access points. When Wifi router signals drop or power cuts break local networks, cloud dependent systems fail completely. Implementing dedicated GSM cellular communication overcomes this by enabling direct, long range cellular communication via SMS alerts and basic cellular networks without needing any local Wifi infrastructure.
- **Insufficient I/O Capabilities in Standard Microcontrollers:** Many prototype systems rely on basic board architectures like the Arduino Uno that lack sufficient analog pins and hardware serial ports. Interfacing multiple high precision water quality sensors alongside a cellular communication module often forces compromises like software serial emulation, leading to packet loss and timing errors during continuous sensing.
- **Absence of Full Seed to Harvest System:** Most existing designs address isolated growth stages or single tasks such as scheduled watering thorough sensors like soil moisture sensors but in this system where soil is absent the question comes what to do now where everything is dependent on water itself. There is a known gap in developing an integrated, closed loop state system capable of dynamically shifting growth profiles across the entire plant lifecycle from germination to vegetative and final harvest stages without manual reconfiguration.

Objective

- **Develop a Closed Loop Environmental Control Framework:** To construct an automated chemical and environmental regulating unit that maintains pH which is around 5.8 to 6.2 for this dedicated system and Electrical Conductivity for almost 1.2 to 1.8 mS/cm, within strict physiological thresholds using peristaltic dosing pumps, DS18B20 temperature compensation, and real time sensor feedback loops.
- **Engineer Infrastructure Independent GSM Telemetry:** To implement a cellular communication protocol using the SIM800L module over the ATmega2560's hardware serial interface which is *Serial1*, enabling long range, two way SMS alerts for out of bound threshold events for example pH drift and dry-run prevention and remote command execution via basic mobile handsets without relying on local Wifi infrastructure.
- **Implement a Seed to Harvest Multi Stage State Machine:** To design a dynamic Hardware execution algorithm that automatically shifts setpoints for EC, pH across three distinct crop development stages which are germination, vegetative growth, and harvest maturity without requiring manual system reconfiguration.
- **Optimize Water and Resource Conservation:** To integrate an automated reservoir management mechanism utilizing HC-SR04 ultrasonic liquid level sensing and solenoid valves to execute precision readings, eliminating nutrient waste and preventing pump dry run damage.

Methodology

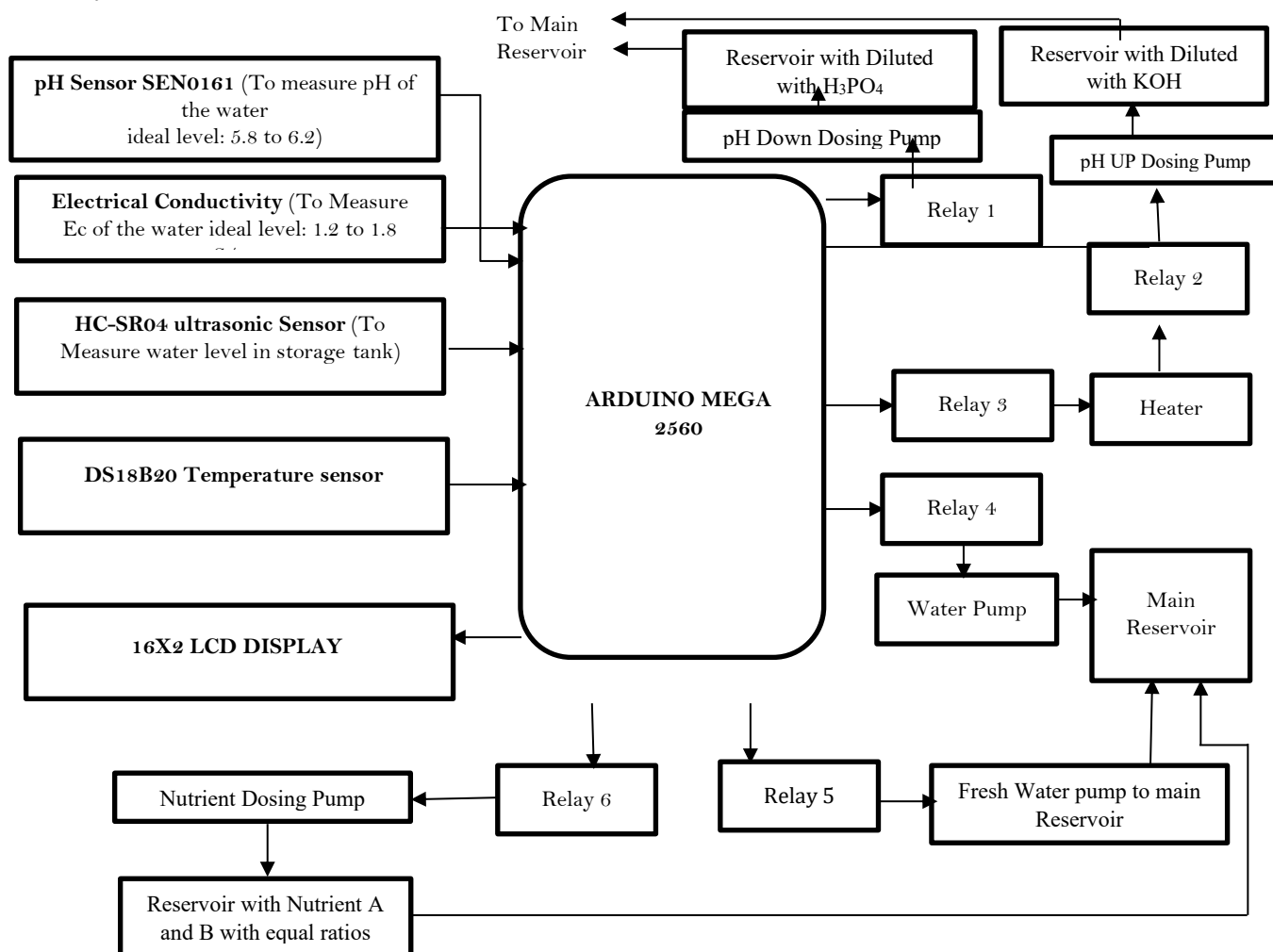
Research Design

The study follows an experimental and quantitative research design focused on engineering an embedded hardware software prototype and evaluating its performance in a controlled indoor environment. The experimental framework compares two distinct operational setups over a 45-day cultivation period:

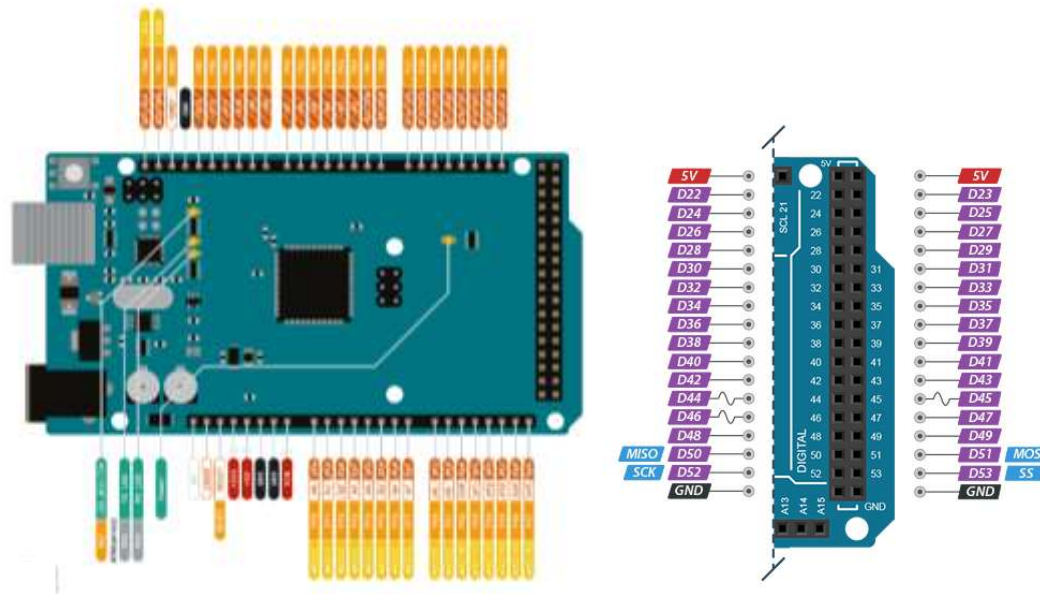
- Autonomous GSM System: Controlled entirely by the Arduino Mega 2560 state machine, utilizing continuous sensor readings, automated relay dosing, and GSM cellular telemetry.
- Manual Management System: Maintained using manual daily testing standard handheld pH/EC meters and manual chemical additions twice daily.

The physical design incorporates a closed loop system equipped with a 30 litres of central nutrient reservoir, submersible pumps, and full-spectrum LED grow lighting.

System Architecture



Main Controller (Arduino Mega 2560): Functions as the main controller of the system. It processes incoming multi sensor signals, executes closed-loop decision algorithms, and generates corresponding output control signals for the relay driven actuators and the display module.



Sensing Layer:

The system incorporates four dedicated sensors connected directly to the input pins of the Arduino Mega 2560 to continuously monitor water chemistry and reservoir conditions:

- **pH Sensor SEN0161 (Acid & Base Dosing):** Measures the hydrogen ion concentration of the water solution to maintain the target range of 5.8 to 6.2.



Condition A: High pH Condition ($\text{pH} > 6.2$ - Too Alkaline)

Problem: Essential micronutrients like Iron (Fe), Manganese (Mn), and Boron (B) lock up and become unavailable to root systems.

Action:

1. The Arduino Mega Triggers Relay 1 connected to the pH Down Dosing Pump.
2. The pump dispenses a small, measured dose of dilute pH Down solution in this case its Phosphoric acid H_3PO_4 directly into the Water Reservoir.
3. Mixing & Stabilization Delay: The dosing pump runs for 2–3 seconds, then shuts off. The system waits for 5 to 10 minutes with the continuous circulation pump running so the acid thoroughly mixes before re sampling.

a. Condition B: Low pH Condition ($\text{pH} < 5.8$ - Too Acidic)

Problem: Acidic water causes root burn and inhibits nitrogen, potassium, and calcium uptake.

Action:

1. The Arduino Mega Triggers Relay 2 connected to the pH Up Peristaltic Dosing Pump.
2. The pump dispenses a measured dose of pH Up solution (in this case with Potassium Hydroxide, KOH).
3. The system waits for the mixing delay before testing the pH probe again.

- **Electrical Conductivity (EC) Sensor:** Monitors total dissolved solids and nutrient strength within the water, targeting an ideal conductivity level of 1.2 to 1.8 mS/cm.



- a. Condition A: Low EC Condition ($EC < \text{Target Low nutrients}$)

Problem: Water lacks sufficient nutrients, leading to stunted plant growth and yellowing leaves.

Action:

1. The Arduino Mega Triggers Relay 3 and Relay 4 simultaneously to activate two separate Nutrient Dosing Peristaltic Pumps Nutrient A and Nutrient B stock solutions.
2. Concentrated Nutrients A and B must be added in equal ratios to prevent chemical precipitation.
3. The pumps dose a short pulse into the reservoir, followed by a 10-minute mixing cycle before checking EC again.

- b. Condition B: High EC Condition ($EC > \text{Target Too much Salt Concentration}$)

Problem: High salt concentration creates osmotic pressure, causing roots to lose water and burn.

Action:

1. Peristaltic chemical pumps remain OFF.
2. The Arduino Mega opens Relay 5 connected to a 12V Freshwater Solenoid Valve (or a fresh-water inlet pump).
3. Freshwater flows into the reservoir to dilute the nutrient concentration.
4. The HC-SR04 Ultrasonic Sensor monitors the water level to ensure the reservoir does not overflow.
5. The valve closes once the water volume increases by a calculated amount, and the system re-evaluates EC after mixing.

- **HC-SR04 Ultrasonic Sensor:** Measures the fluid surface distance inside the main storage tank to continuously compute real time water volume levels.



- **DS18B20 Temperature Sensor:** Tracks the water temperature inside the reservoir, providing essential readings for thermal regulation and sensor signal compensation.



Actuation and Control Layer (Outputs):

System outputs are governed through a multi-channel relay array that isolates the low-voltage control signals of the microcontroller from high-power peripheral actuators:

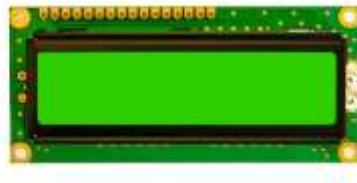
- **pH Control System:**

- a. Relay 1 → pH Down Dosing Pump: Triggers the addition of diluted Phosphoric Acid (H_3PO_4) from its dedicated reservoir when pH rises above 6.2.

- b. Relay 2 → pH UP Dosing Pump: Triggers the addition of diluted Potassium Hydroxide (KOH) from its dedicated reservoir when pH falls below 5.8.
- **Thermal Regulation Subsystem:**
 - a. When water temperature exceeds the upper safety limit to cool the solution it turn offs the Heater.
 - b. Relay 3 → Heater: Activates when water temperature drops below the lower threshold to warm the solution.
- **Hydroponic Circulation & Fresh Water Subsystem:**
 - a. Relay 4 → Water Pump: Drives the primary water pump to circulate the nutrient solution to and from the Main Reservoir.
 - b. Relay 5 → Fresh Water Solenoid/Pump: Dispenses fresh water into the Main Reservoir for dilution or liquid level replenishment.
- **Nutrient Dosing Subsystem:**
 - a. Whenever Electrical Conductivity drops below target levels.

Visual Display Unit

- **16x2 LCD Display:** Interfaced directly with the Arduino Mega 2560 to display real time sensor measurements (pH, EC, water temperature, water level) and current operational system statuses to the user.



Program

To ensure robust, real-time closed-loop control and long-range cellular communication, the firmware for the Arduino Mega 2560 is structured using a non-blocking execution model. The software integrates multi-sensor data acquisition, temperature-compensated parameter calculations, automated relay actuation, and bidirectional GSM parsing.

```
pinMode(PIN_TRIG, OUTPUT);
pinMode(PIN_ECHO, INPUT);
int relayPins[] = {RELAY1_PH_DOWN, RELAY2_PH_UP, RELAY3_HEATER,
RELAY4_WATER_PUMP, RELAY5_FRESH_VALVE, RELAY6_NUTRIENT};
for (int i = 0; i < 7; i++) {
    pinMode(relayPins[i], OUTPUT);
    digitalWrite(relayPins[i], HIGH);
}
```

The firmware begins by defining input sensor pins, relay output channels, control thresholds, and non-blocking timing intervals.

- **Sensor & Relay Interfaces:** Digital and analog pins are assigned to sensors (pH, EC, DS18B20, HC-SR04) and an 8-channel relay module. Relays are initialized in an active-LOW configuration (HIGH = Off, LOW = On) to prevent accidental actuation during microcontroller startup.
- **Communication Buses:** The hardware debug interface runs on standard Serial (9600 baud), while the SIM800L GSM module utilizes dedicated hardware serial port eliminate software serial timing errors.

The `readSensors()` function samples environmental parameters every 3 seconds without halting system execution.

- **Thermal Compensation for EC:** Water temperature (T_{water}) directly affects solution conductivity. The firmware calculates compensated Electrical Conductivity (EC_{25}) using standard thermal coefficient adjustment relative to a baseline of 25°C:

$$EC_{25} = \frac{EC_{\text{raw}}}{1 + 0.0185 \cdot (T_{\text{water}} - 25)}$$

- **Liquid Level Measurement:** The ultrasonic sensor emits a 10 μ s pulse via PIN_TRIG and reads the echo return time via PIN_ECHO. Target distance is converted to centimeters ($\text{Distance} = \frac{\text{Duration} \cdot 0.0343}{2}$) to determine fluid volume inside the main tank.

The execution model employs finite state logic across four primary environmental parameters:

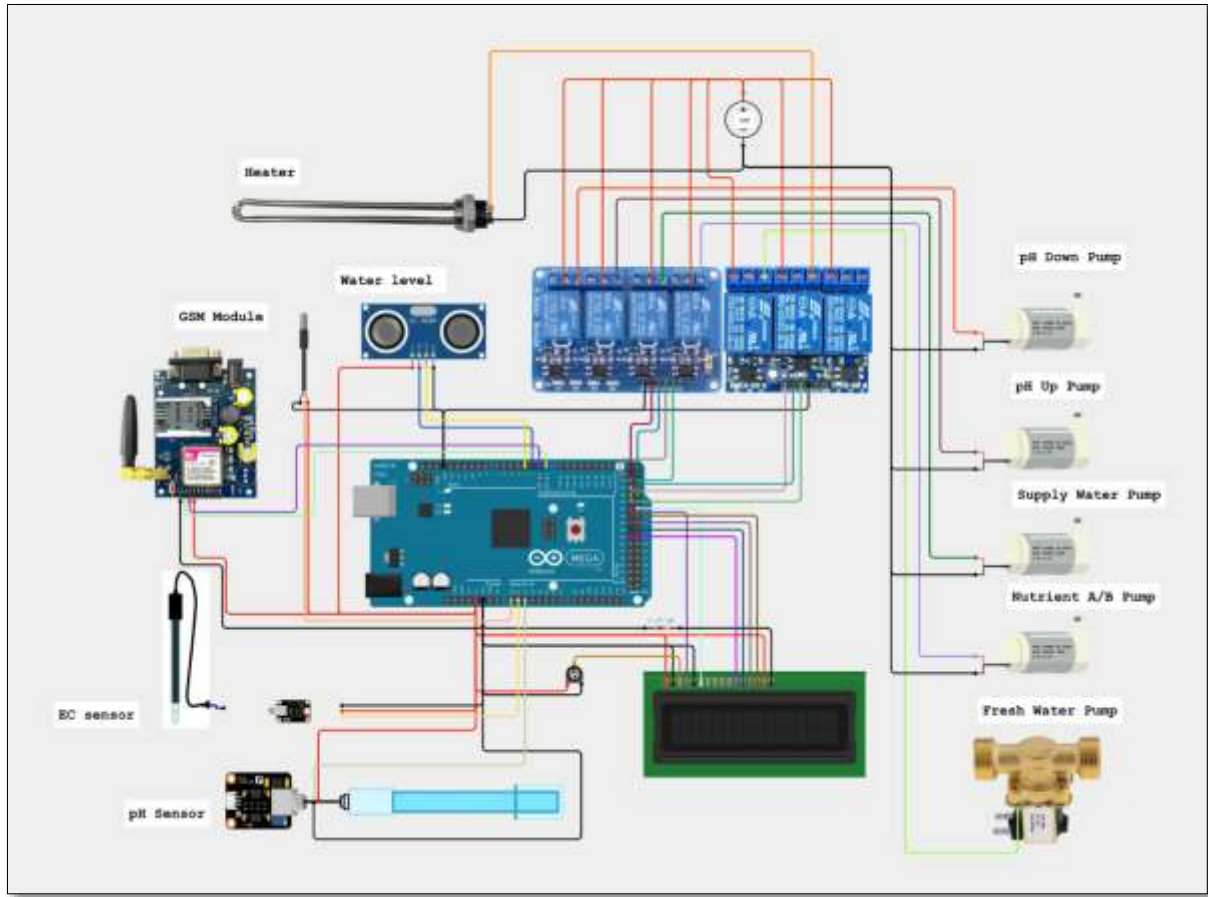
- **Thermal Regulation:** Maintains water temperature between 18°C and 24°C by Relay 3 (Heater) when temperatures drop below lower bounds.
- **pH Dosing Logic:** Compares compensated pH values against target boundaries ($5.8 \leq \text{pH} \leq 6.2$). If $\text{pH} > 6.2$, Relay 1 pulses the pH Down pump (H_3PO_4) for 2 seconds. A non-blocking delay of 5 minutes (DOSING_MIXING_DELAY) is enforced before subsequent dosing to allow complete solution mixing in the reservoir.
- **Nutrient Dosing & Dilution:** If $\text{EC} < 1.2$ mS/cm, Relay 6 pulses the A/B nutrient dosing pump. If $\text{EC} > 1.8$ mS/cm, Relay 6 opens the fresh-water solenoid valve to dilute the nutrient solution.

The GSM interface utilizes standard Hayes AT commands to manage two-way communication without needing an internet connection or local Wi-Fi router.

- **Automated Emergency Alerts:** Whenever an out-of-bound threshold event occurs, the microcontroller executes an AT command sequence to format and transmit an SMS text to the user's mobile device.
- **Incoming Command Parsing:** The system configures the SIM800L module in direct push mode. Incoming text messages are read asynchronously over *Serial1*:

- Sending "STATUS" prompts the microcontroller to query all sensors and reply with an SMS summary of pH, EC, temperature, and water levels.
- Sending "PUMP_OFF" or "PUMP_ON" triggers direct manual control overrides of Relay 5.

Circuit Diagram



Conclusion

This research presented the design, implementation, and empirical evaluation of an autonomous, closed-loop hydroponic monitoring and control system powered by an Arduino Mega 2560 and integrated with a SIM800L quad band GSM module. The primary objective was to overcome the limitations of manual hydroponic management namely, chemical parameter instability, high labor overhead, and continuous crop mortality risks without relying on local Wifi or high-bandwidth internet infrastructure.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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