Design and Implementation of a Water Purification and Quality Monitoring System

1 Project Overview

Objective: To design an automated water purification and quality monitoring system prioritizing robust filtration performance, sensor accuracy, and operational safety.

The key features of the system include:

- Multi-stage filtration (Sediment, Carbon, and post filtration).
- UV treatment for disinfection.
- Real-time IoT quality monitoring.
- Automated self-protection mechanisms.

2 System Architecture and Hardware Layout

The system is made up of four different filters that operate in the pre-filtration phase, a UV lamp to kill microbial contaminants, and various sensors at different stages used to monitor the system and support the automation of the different actuators.

2.1 Hardware Block Diagram

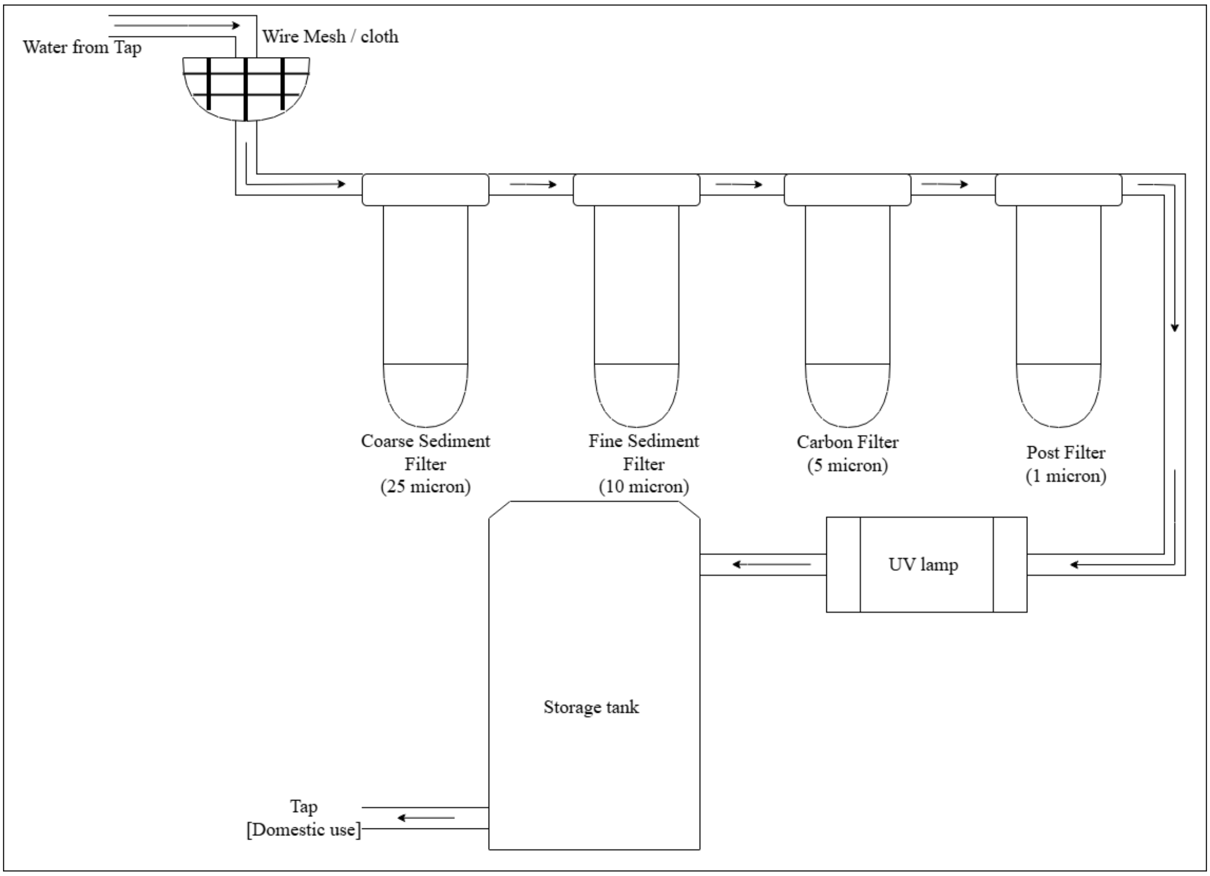


Figure 1: Hardware block diagram of the system.

2.2 Overall system representation

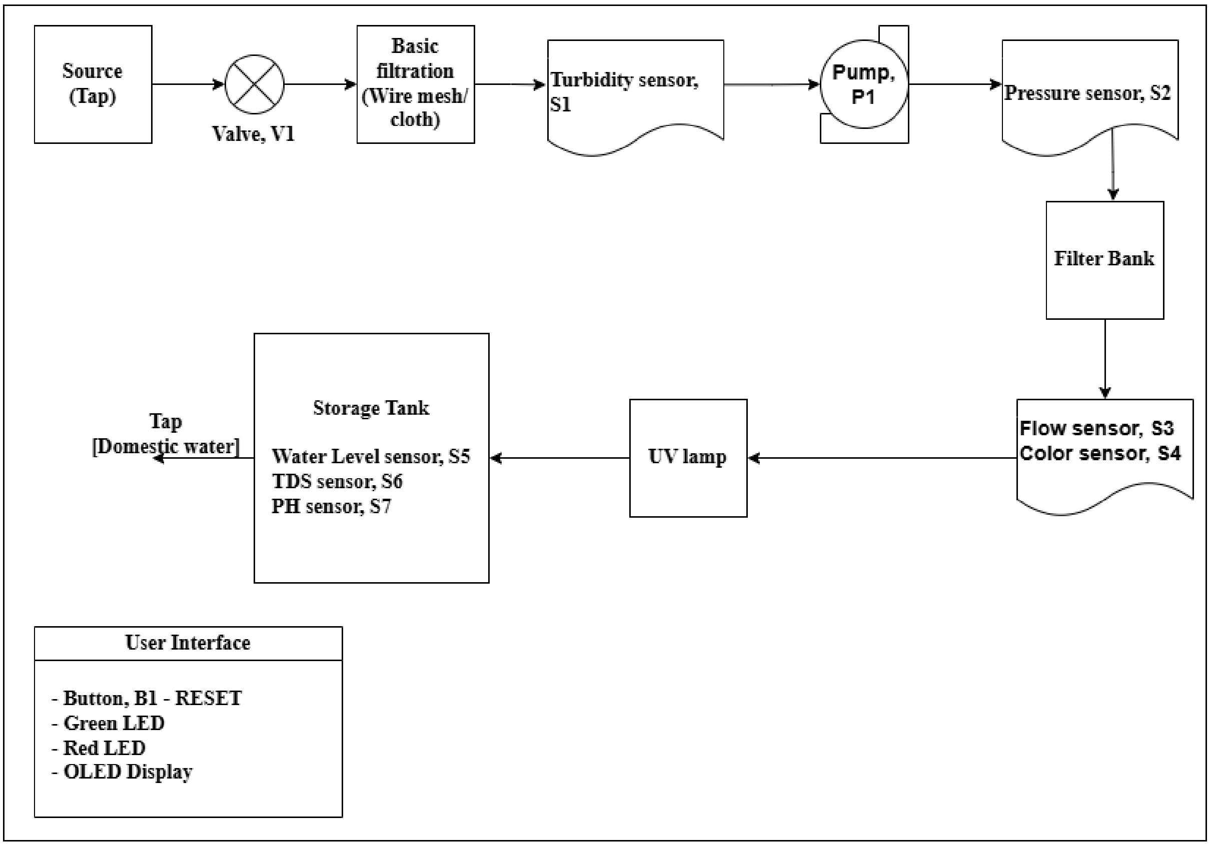


Figure 2: Overall system schematic representation.

During this stage, raw water is treated before storage. The process includes:

- **Filtration:** Water is drawn by pump P1 and passed through a filter bank consisting of two sediment filters (25 µm and 10 µm), an activated carbon 5 µm filter, and a 1 µm post-filter.
- **System Protection:** A pressure sensor (S2) and flow sensor (S3) monitor the system conditions to detect clogs.
- **Disinfection:** A UV lamp is installed after the filter bank to reduce microbial load before water enters the storage tank.

3 System Operational Modes

The system is designed with a microcontroller to monitor parameters and automate operations.

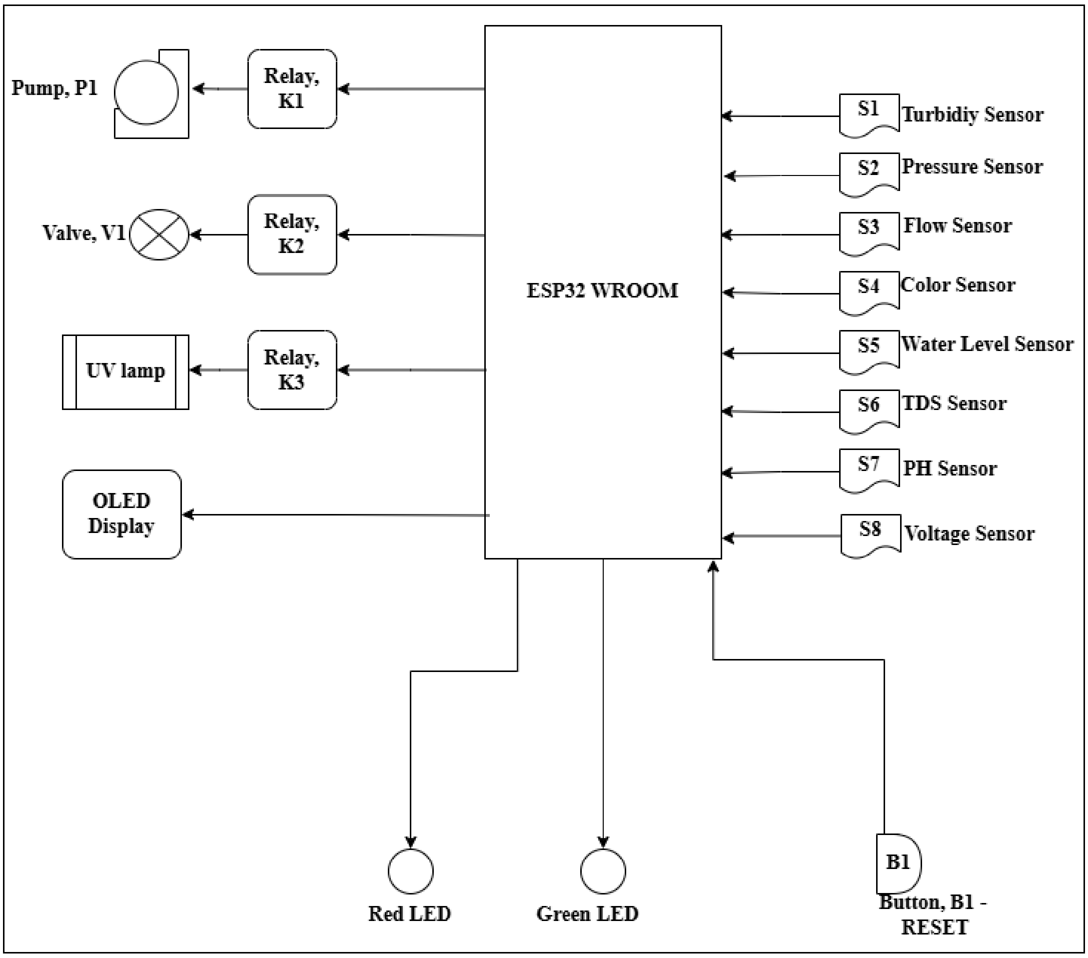


Figure 3: Microcontroller and component integration.

The microcontroller operates in three distinct modes to ensure safety, fault isolation, and energy efficiency:

3.1 Filtration Mode

Objective: To automatically fill the storage tank while protecting hardware components.

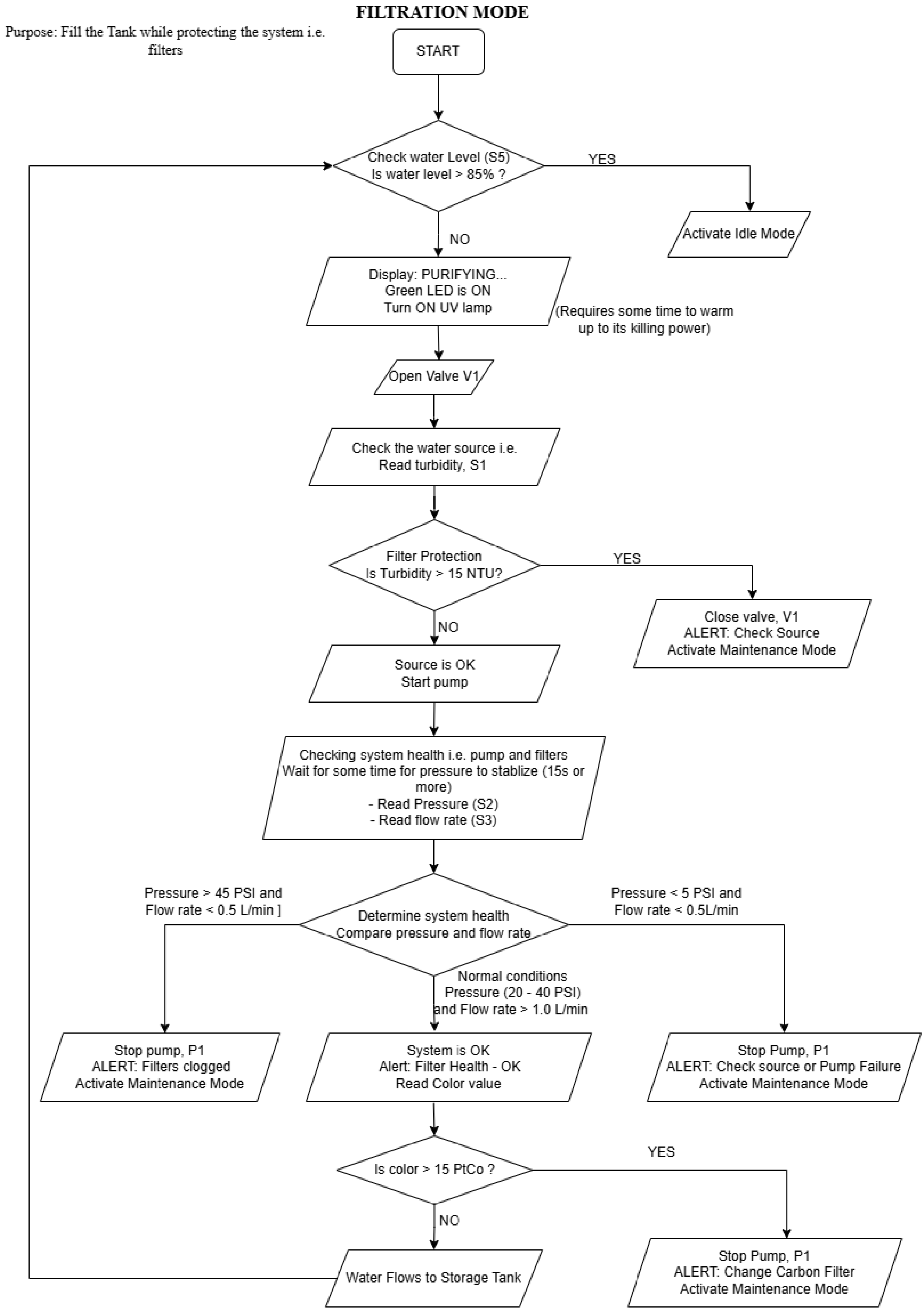


Figure 4: Filtration mode.

- **UV Warm-up:** The UV lamp activates before the pump starts to ensure no untreated water enters the storage tank.

- **Clog and Dry Run Detection:** The system differentiates faults by comparing Pressure (S2) and Flow Rate (S3).
- **Source Quality:** Turbidity (S1) is checked to prevent fouling the filters. Color (S4) is monitored to ensure effective UV transmission.

3.2 Idle Mode

Objective: To ensure energy conservation while monitoring the system.

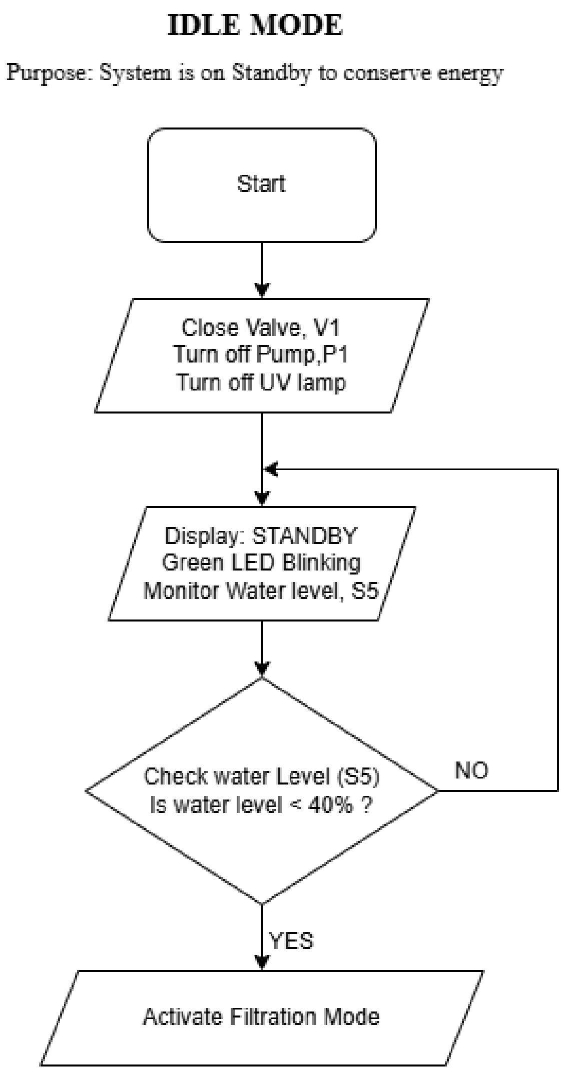


Figure 5: Idle mode.

- Activated when the storage tank is full (water level > threshold).
- High-power consumption components (Pump P1, UV Lamp) are turned OFF.
- **Continuous Monitoring:** The system wakes periodically to check the tank water level.

3.3 Maintenance Mode

Objective: To lock the system during critical faults.

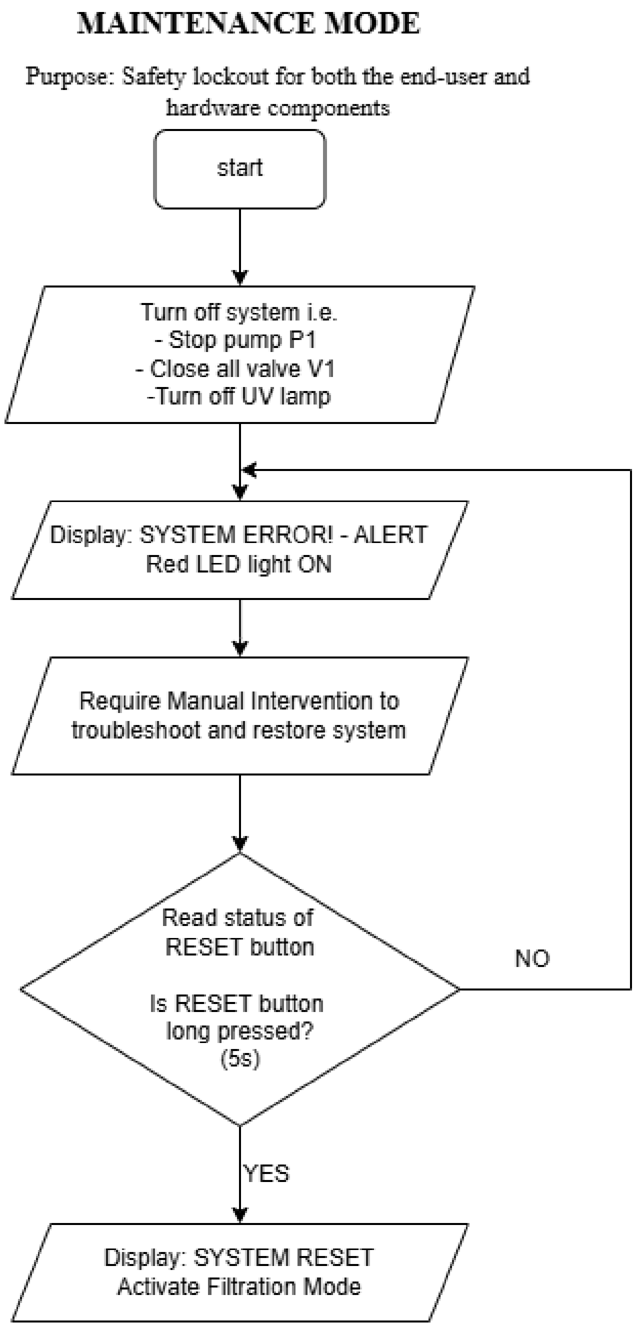


Figure 6: Maintenance mode.

- Activated by critical errors such as clogged filters or unsafe water parameters.
- System enters a full shutdown state, requiring manual intervention/reset from an operator.

4 User Interface and Water Quality Standards

4.1 Status Indicators

The system communicates its operational state using an LED light interface and an OLED screen.

Table 1: System Status Indicators

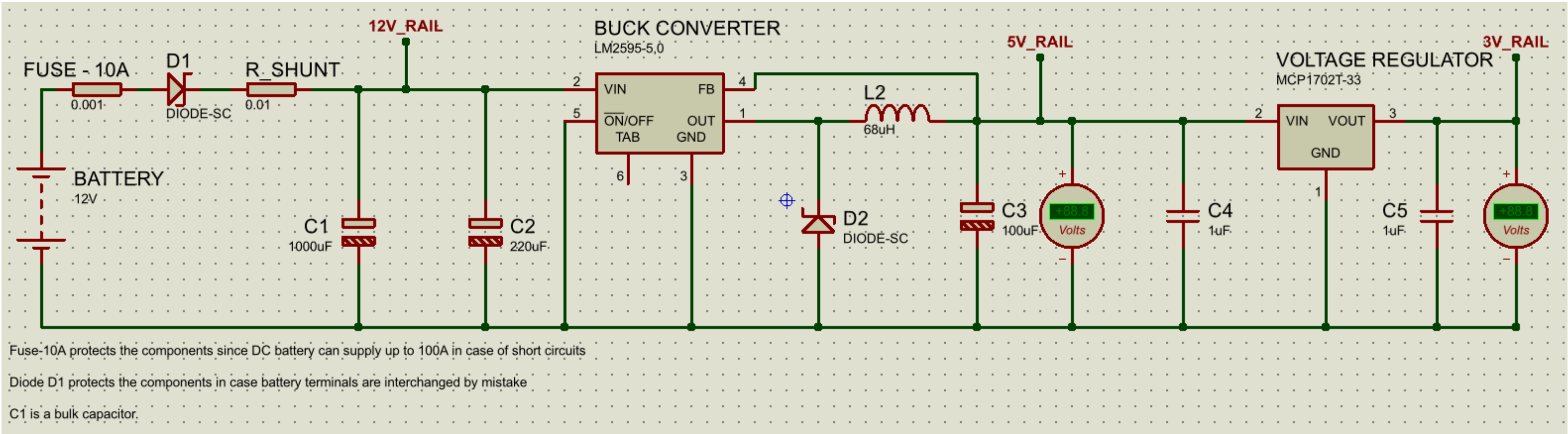
LED Color	**Mode**	**Description**
Green blinking	Idle	System ready / Tank full
Green	Filtration	System active and purifying
Red	Maintenance	Critical fault (Technician required)

5 Electrical Design and Simulation

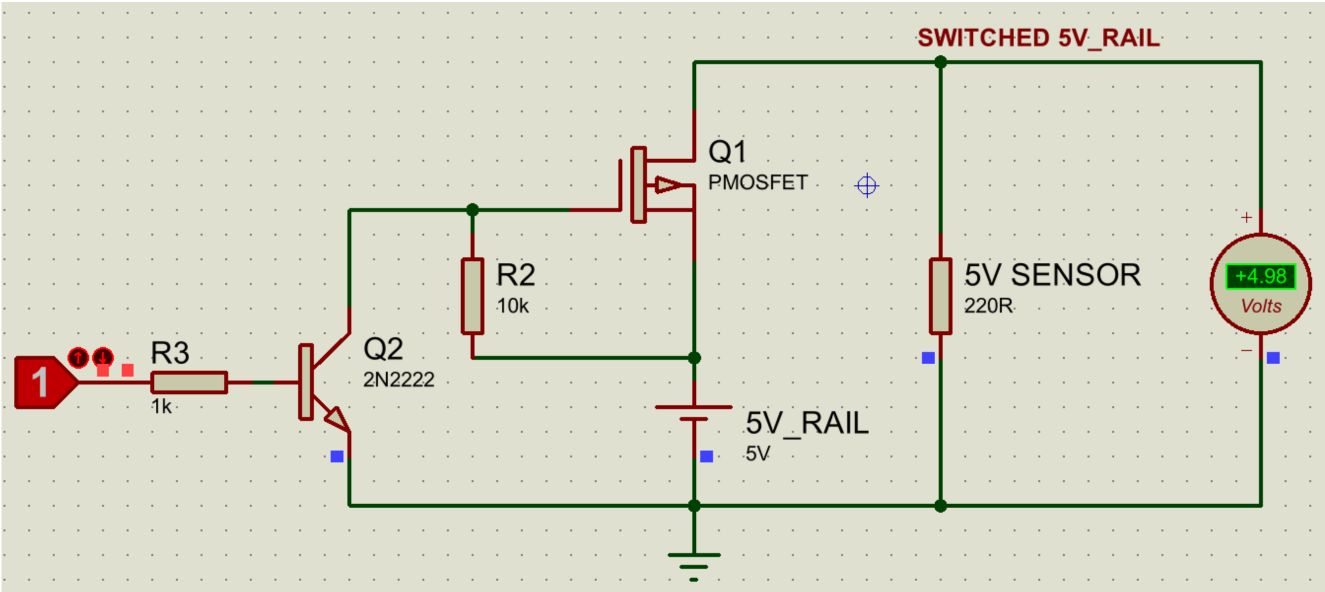
The PCB design integrates power management, signal conditioning for sensors, and actuator control. Simulations were conducted to verify circuit stability and safety before fabrication.

5.1 Power Management Simulation

The system is powered by a 12V Battery. The design includes a step-down conversion from 12V to 5V and 5V to 3.3V. Additionally, a **Switched 5V Rail** using a PMOS high-side switch allows the MCU to cut power to external sensors to conserve battery i.e. the sensors are only activated when readings are to be taken.



(a) Main Power Supply: 12V to 5V/3.3V conversion with protection.



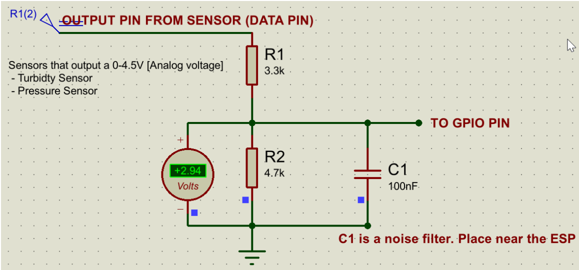
(b) Switched 5V Rail: Logic-controlled power distribution for sensors.

Figure 7: Power Management Simulations.

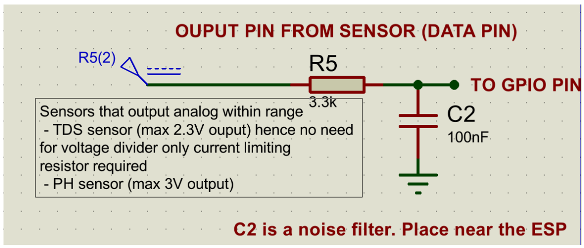
5.2 Sensor Signal Conditioning

The system interfaces with three distinct types of sensor outputs. Signal conditioning circuits were simulated to ensure the 3.3V ESP32 receives safe and noise-free data:

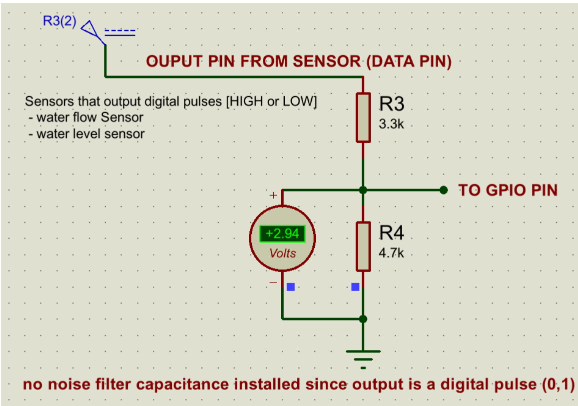
- **Analog 0-4.5V:** Voltage divider required (Turbidity/Pressure).
- **Analog 0-3V:** Direct connection with RC filter (TDS/pH).
- **Digital Pulse:** Current limiting and pull-up/down logic (Flow/Level).



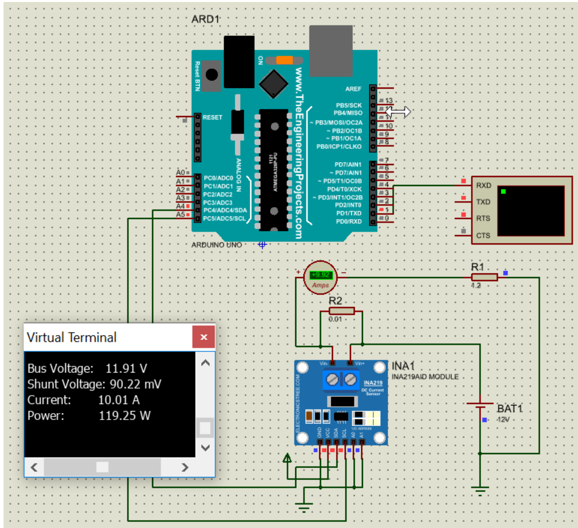
(a) 5V Analog Sensor (Voltage Divider).



(b) 3V Analog Sensor (Direct).



(c) Digital Sensor Interface.



(d) Extending the range of INA219.

Figure 8: Sensor signal conditioning and interface simulations.

5.3 Actuator Control Logic

High-current components (Pump, UV Lamp) are isolated from the MCU using Relays and NPN Transistors (2N2222). The simulation verifies that a logic signal from the MCU successfully switches the 12V load.

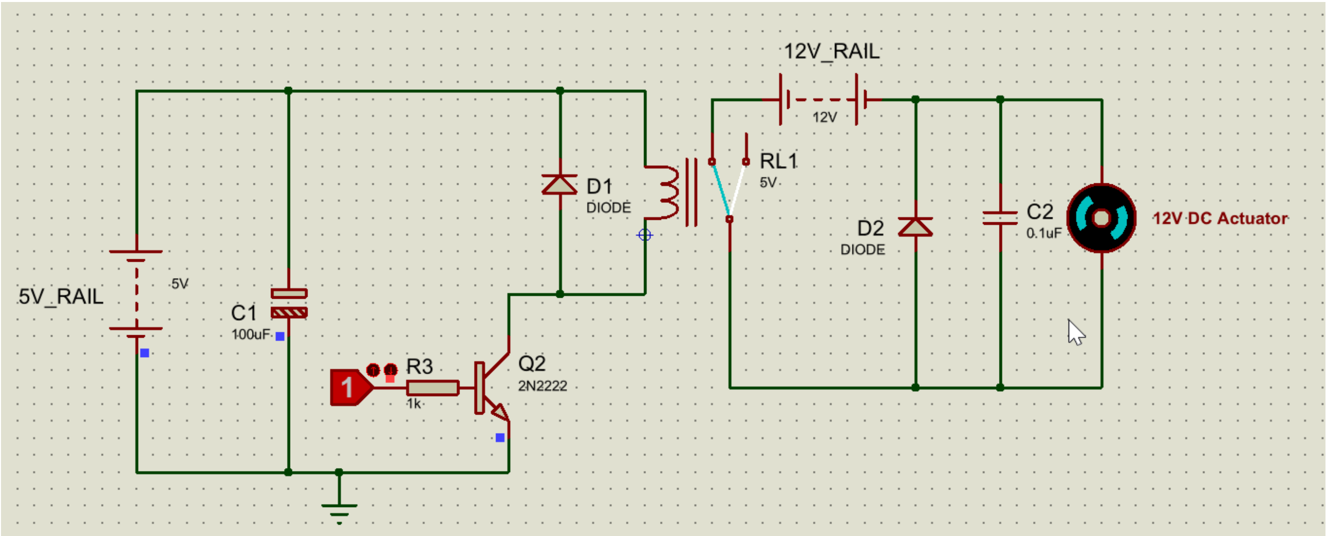


Figure 9: Actuator driver circuit with Relay and NPN transistor.

6 Bill of Materials Summary

6.1 External Hardware & Sensors

Table 2: Key External Components

Category	Component	Function
Filtration	25μm, 10μm, 5μm (Carbon), 1μm	Multi-stage particulate & chemical removal
Sterilization	12W Stainless Steel UV Lamp (12V)	Final disinfection
Actuators	Seaflo 12V Diaphragm Pump	Water delivery
	Solenoid Valve (12V)	Flow control
Sensors	Turbidity, TDS, pH, Color	Water Quality Monitoring
	Pressure, Flow, Level (Ultrasonic)	System Status Monitoring
Power	INA219 Voltage/Current Sensor	Real-time power consumption tracking

6.2 PCB Components

The custom PCB is built around the ESP32-S3 WROOM module. Total estimated cost for external hardware is approx. $370, and PCB components approx. $37.

Table 3: Key PCB Electronic Components

Subsystem	**Component**	**Specification**
MCU	ESP32-S3-WROOM-1	Wi-Fi/BT enabled, Dual-core
Power	LM2595-5.0	3A Buck Converter (12V $\rightarrow$ 5V)
	MCP1702	LDO Regulator (5V $\rightarrow$ 3.3V)
Switching	Songle Relay (SRD-05VDC)	5V Coil, switches 12V loads
	2N2222A	NPN Transistor for relay driving
Connectors	KF128 / KF350	Screw terminals for external wiring