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Aqua Phoenix: An Integrated Hybrid Greywater Purification System Utilizing Waste-Derived Filtration Media and IOT-Based Real-Time Monitoring

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Abstract

The rapid pace of urbanization and depleting freshwater resources have stressed the need for effective and sustainable ways of managing wastewater. The present research work deals with "AquaPhoenix," a new, low-cost, hybrid greywater purification system that introduces a biological rhizofiltration mechanism using Lemna minor in combination with some physicochemical processes comprising coagulation, activated carbon filtration, and membrane technology. Uniquely, filtration media used in this treatment system will be prepared from agricultural and industrial wastes to contribute toward a circular economy. For enhancing operational efficiency and transparency in data, the treatment system has been integrated with an IoT-based framework, which facilitates real-time monitoring of water quality parameters. The experimental results showed a significant reduction in Turbidity from >100 NTU to <5 NTU, Total Dissolved Solids from ~3000 ppm to 61 ppm, and microbial load, therefore bringing the treated water in line with WHO and BIS potable standards. This research adds validity to the waste-to-resource model for decentralized water treatment.

Keywords: Greywater Recycling, Rhizofiltration, Circular Economy, IoT Monitoring, Membrane Filtration, Sustainable Water Management.

1. Introduction

The growing global crisis on water scarcity has India grappling with acute challenges due to the depleting and pollution of its groundwater. Greywater-wastewaters from baths, sinks, and washing machinesconstitutes 60-70% of domestic wastewater but is largely unexploited; most of the time, it mixes with blackwater in sewage lines. These conventional treatment plants are energy-intensive and require expensive infrastructure, making them inaccessible for decentralized rural or small-scale urban applications.

At the same time, there exists a dilemma in waste management. India produces more than 600 million tonnes of agricultural residue and huge quantities of industrial waste every year. The "AquaPhoenix" proposes a symbiotic solution: making use of waste products-agricultural biochar and industrial steel/PVC scraps-to build a filtration system for greywater. This research undertakes the task of developing a multistage purification protocol strengthened by IoT automation with a view to achieving reliability and scalability, making waste a key resource.

2. Materials and Methods

2.1 Experimental Setup and Sample Collection

A composite greywater sample was collected from the three primary domestic sources of greywater: washbasins, kitchen sinks, and bathrooms. The organic matter, suspended solids, oils, surfactants, and microbial contaminants were the contents in the sample.

2.2 Purification Scheme

Treatment train The treatment train comprises ten distinct stages:

1. Preliminary Screening: A 1000-micron wire mesh removes major particulate matter.

2. Coagulation & Sedimentation: Iron (III) chloride ($FeCl_3$) is added as a coagulant. The solution is left standing for 2 hours to allow the suspended solids and heavy metals to settle down.

3. Rhizofiltration (Biological Treatment): A man-made wetland is implemented with duckweed Lemna minor. The plants absorb nitrates, phosphates, and heavy metals like Pb, Hg, and Cd by means of active transport and bioaccumulation for a retention period of 5-6 days.

4. **Adsorption:** The water passes through a bed of granular activated carbon (obtained from agricultural residues), which removes volatile organic compounds (VOCs), oil, and odour.

5. Ion Exchange: The cation exchange provided by the zeolite bed removes ions causing hardness (Ca^{2+}, Mg^{2+}) and other remaining heavy metals.

6.RO/UF: Membrane Filtration

- **Reverse Osmosis (RO):** The polypropylene semi-permeable membrane filters out TDS and viruses to 0.0001 microns.
- **UF**: 0.01–0.1 microns ultrafiltration is a secondary barrier, ensuring the removal of residual bacteria and colloids.

7. Remineralization & pH Stabilization: RO water, normally acidic and deprived of minerals, passes through a bed of limestone ($CaCO_3$) to neutralize pH and replenish Calcium.

8.Disinfection: Chlorine tablets are administered to ensure zero microbial viability.

9. Thermal Treatment: Final boiling is a redundant step to ensure safety against pathogens.

2.3 IoT and Automation Integration

An ESP32 microcontroller-based IoT framework was integrated to transition from a manual prototype to a smart system.

- **Sensors:** Industrial-grade sensors were fitted at critical junctions for parameters like pH, Turbidity, TDS, Water Level, and Flow Rate.
- **Automation Logic:**
  - Level Control: Ultrasonic sensors trigger inlet pump when the raw water tank is full and outlet pump when the treated tank is at capacity.
  - Quality Feedback: If the values of TDS or Turbidity exceed the threshold, for example, > 500 ppm TDS, then a solenoid valve automatically diverts water back to sedimentation for re-treatment.
- **Data Logging:** Sensor data are sent over Wi-Fi to a cloud dashboard, Blynk or ThingSpeak, which enables real-time remote monitoring of water quality parameters.

3. Observations and Results

We carried out physicochemical testing of the water before and after treatment. Results indicate a sharp improvement in quality, at present conforming to both WHO and BIS standards.

Table 1: Comparative Water Quality Analysis

Parameter	**Initial (Untreated)**	**Final (Treated)**	**BIS Limit (Acceptable)**	**Efficiency/Remarks**
pH	6.35	7.5	6.5 – 8.5	Stabilized to neutral/alkaline range.
TDS (ppm)	2981	61	500	**97.9% reduction**, well within potable limits.
Hardness (mg/L)	250	25	200	Hardness significantly reduced.
Turbidity	High (Opaque)	Clear	1 NTU	Visually crystal clear.

Parameter	Initial (Untreated)	Final (Treated)	BIS Limit (Acceptable)	Efficiency/Remarks
Sulphate (mg/L)	200	5	200	Reduced well below permissible limits.
Microbial Load	Positive	Negative	Absent	Pathogens successfully eliminated.
Electrical Conductivity	5962 µS/cm	~100 µS/cm	-	Drastic reduction indicates removal of ions.

4. Discussion

4.1 Effectiveness of Hybrid Filtration

Data validates the hypothesis that biological and chemical methods employed in conjunction achieve better performances. The Rhizofiltration stage was particularly successful in removing nutrient load (Nitrates/Nitrites), thus preventing fouling of RO membranes in the downstream stages. The high drop in TDS from 2981 ppm to 61 ppm confirms efficiency at the RO stage, while the limestone bed corrected the pH from an acid 4.91 mid-process value back to a healthy 7.5.

4.2 Circular Economy and Sustainability

Whereas conventional plants depend on virgin raw materials, AquaPhoenix makes use of agricultural waste biochar and industrial scrap. Moreover, the sludge produced after sedimentation is rich in organic content and can thus be reused as manure. The paper further suggests that Geobacter bacteria may be used in the future to convert the organic breakdown into bio-energy, which could neutralize part of the energy usage by the pumps. 4.3 IoT Reliability IoT sensors provided continuous streams of data, detecting fluctuations that would be missed with manual testing. The feedback loop ensured that substandard water was never allowed to enter into the final storage tank; this was a necessary feature for a commercial implementation.

5. Conclusion

The AquaPhoenix system is a proof of concept that high-contamination greywater can be restored to potable water standards with an economical and waste-derived infrastructure. The treated water is IS 10500:2012 (BIS) and WHO compliant. This system combines nature-based solutions like Lemna minor with powerful membrane filtration and intelligent IoT monitoring, thus creating a model that can be easily scaled up for housing societies and industries. It not only tackles the issue of water scarcity but also of waste management by asserting that "waste is merely a misplaced resource."

Future Scope

1. **The bio-energy Harvesting:** Approach will primarily involve the application of microbial fuel cells with Geobacter species for the power supply to the IoT sensors.
2. **AI Integration**: The establishment of Machine Learning tools for the forecasting of filter choking using the flow rate and turbidity patterns.
3. **Genomic Enhancement:** The study of the genetically engineered duckweed for the super-accumulation of particular industrial toxins will be pursued.

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Appendices

APPENDIX A: SCHEMATIC DIAGRAM OF THE FILTRATION PROCESS

A.1 Process Overview

The AquaPhoenix system utilizes a linear, gravity-assisted and pump-driven multi-stage filtration protocol in order to gradually remove physical, chemical, and biological contaminants. The following schematic depicts sequential flow of greywater through the ten distinct purification modules, from raw collection to final remineralization and disinfection.

A.2 System Flowchart

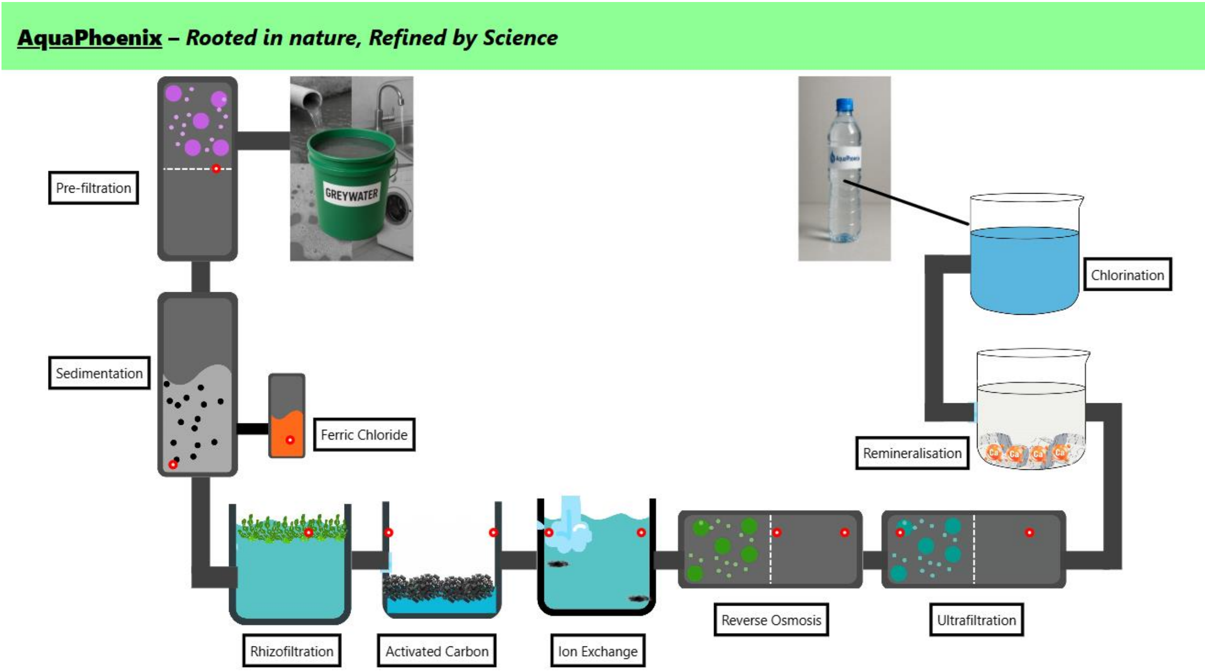

Figure A.1: Comprehensive process flow diagram of the 10-stage AquaPhoenix hybrid filtration system incorporating biological Rhizofiltration with physicochemical treatment units.

A.3 Stage Description

1. **Screening:** Removal of large particulate matter by means of wire mesh.
2. **Sedimentation:** Coagulation using Ferric Chloride ($FeCl_3$) to settle suspended solids.
3. **Rhizofiltration:** Biological uptake of nitrates and heavy metals by Lemna minor (Duckweed).
4. **Activated Carbon:** Adsorption of dissolved organics, oils and odors.
5. **Ion Exchange:** Removal of hardness (Ca^{2+}, Mg^{2+}) and toxic metals by using zeolite media.
6. **Reverse Osmosis:** RO involves the use of 0.0001-micron high-pressure membrane filtration to remove dissolved solids.
7. **Ultrafiltration (UF):** Secondary membrane barrier, 0.01 microns, for colloidal and microbial clearance.
8. **Remineralization:** Passing through a limestone ($CaCO_3$) bed to stabilize pH and replenish the essential minerals.
9. **Disinfection:** Chlorination to ensure complete pathogen elimination.
10. **Final Polishing:** Storage in the "AquaPhoenix" potable water reservoir.

Appendix B: Circuit Diagram of ESP32 IoT Interface.

B.1 Hardware Interface Overview

AquaPhoenix employs an ESP32-WROOM-32 microcontroller as the central processing unit due to its dual-core architecture and onboard Wi-Fi capabilities. The system works with a logic voltage of 3.3V, while sensors and relays are powered through a regulated 5V bus. High-power components (pumps) are electrically isolated using a 4-Channel Relay Module and powered through an external 12V DC source with the purpose of preventing possible voltage spikes from destroying the microcontroller..

B.2 Pin Configuration Map

The following table describes the exact mappings between the ESP32 GPIO pins and the peripheral components as shown in the circuit diagram.

Component	**Type**	**ESP32 Pin**	**Function**
TDS Sensor	Analog Input	**GPIO 34**	Measures Total Dissolved Solids (ADC1)
pH Sensor	Analog Input	**GPIO 35**	Measures acidity/alkalinity (ADC1)
Turbidity Sensor	Analog Input	**GPIO 32**	Measures water clarity (ADC1)
Water Level Sensor	Analog Input	**GPIO 33**	Measures tank fill level (ADC1)
Temp Sensor (DS18B20)	Digital (OneWire)	**GPIO 04**	Measures water temperature
Flow Sensor (Inlet)	Digital (Interrupt)	**GPIO 05**	Measures inlet flow rate (Pulse)
Flow Sensor (Outlet)	Digital (Interrupt)	**GPIO 18**	Measures outlet flow rate (Pulse)
LCD Display (16x2)	I2C Communication	**GPIO 21 (SDA)**	Serial Data Line for Display
	I2C Communication	**GPIO 22 (SCL)**	Serial Clock Line for Display
Inlet Pump (Relay 1)	Digital Output	**GPIO 13**	Controls Raw Water Pump
Outlet Pump (Relay 2)	Digital Output	**GPIO 12**	Controls Treated Water Pump
Ion Pump (Relay 3)	Digital Output	**GPIO 14**	Controls Ion Exchange/Filtration Pump
Emergency (Relay 4)	Digital Output	**GPIO 27**	System Cut-off / Backup Mechanism

B.3 System Circuit Schematic

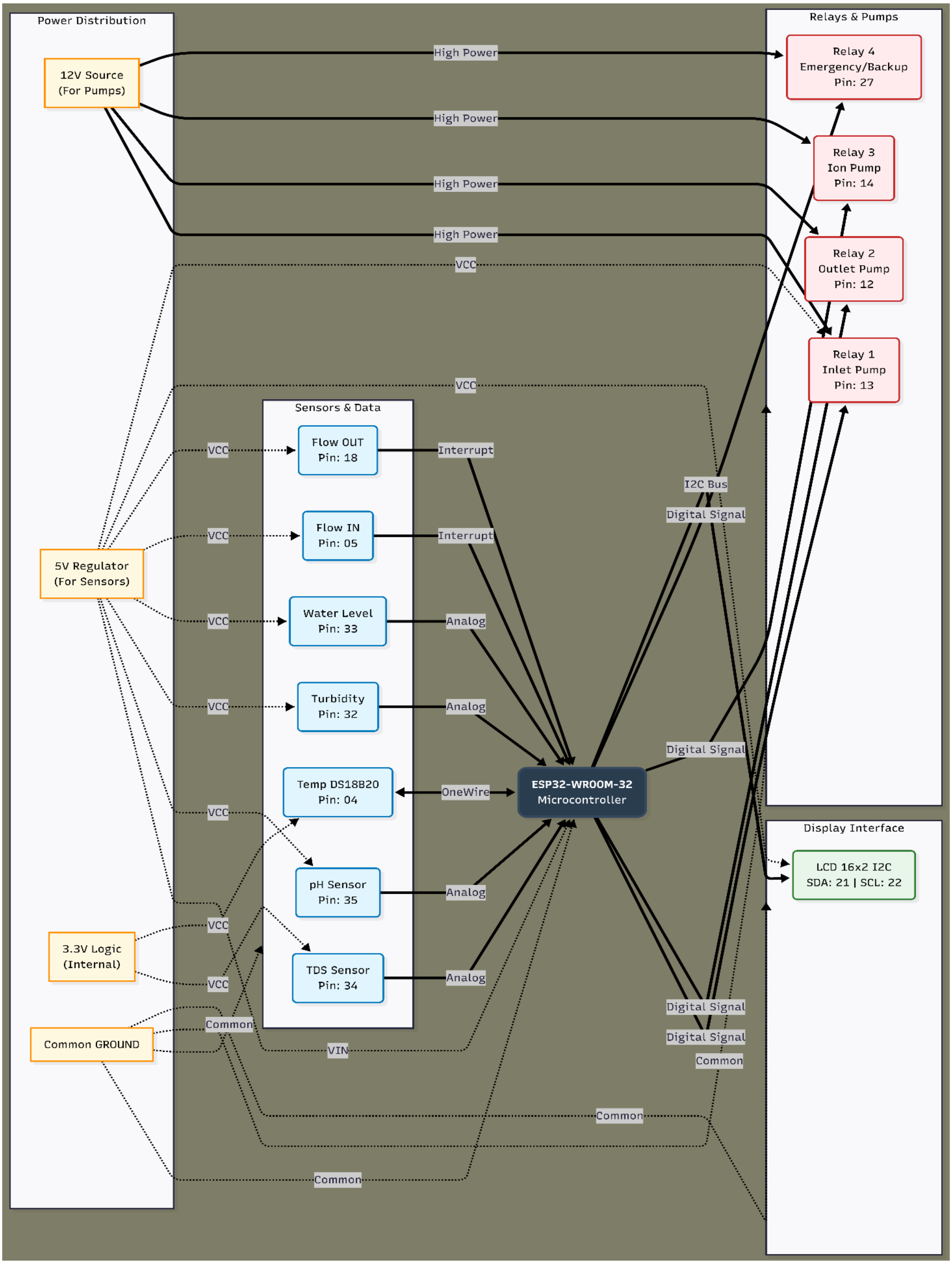

Figure B.1: Block schematic illustrating the power distribution, sensor data acquisition and actuator control logic of the AquaPhoenix IoT system.

B.4 Process Description

1. **Data Acquisition:** The ESP32 polls all analog sensors-TDS, pH, Turbidity, and Level-each in the time interval of 1000ms. It converts the analog voltage into digital values via the ESP32's 12-bit ADC.
2. **Flow Calculation:** The digital pulses, which are proportional to the water flow rate, come from flow sensors. Hardware Interrupts are used in pins 05 and 18 to avoid losing data during high-speed flows.
3. **Control Logic:** The ESP32 responds to sensor data-e.g., if Water Level < 20%-with a digital signal, HIGH or LOW, in order to actuate the appropriate pump via the Relay Module.
4. **Power Isolation:** The schematic emphasizes the isolation of the power domains: 12V for the high-load pumps, 5V for sensors/relays, and 3.3V for the logic level of the ESP32 and specific sensors like TDS/Temp, all ensuring stability in operation.
5. **Telemetry:** All processed data is transmitted wirelessly through Wi-Fi to the cloud dashboard for real-time remote monitoring.

APPENDIX C: PHOTOGRAPHIC EVIDENCE OF WATER SAMPLES (PRE vs. POST TREATMENT)

C.1 Visual Comparison of Water Quality

	
Figure C.1 (Pre-Treatment): Initial greywater sample collected from domestic sources, exhibiting high turbidity, suspended solids, and opaque coloration.	**Figure C.2 (Post-Treatment):** Final purified "AquaPhoenix" water sample after 10-stage filtration, visually clear and compliant with potable standards .

C.2 Experimental Setup & Biological Treatment

Figure C.3 (Apparatus): The complete 10-stage hybrid filtration prototype, integrating automated pumps, IoT sensors, and multi-stage filtration cartridges

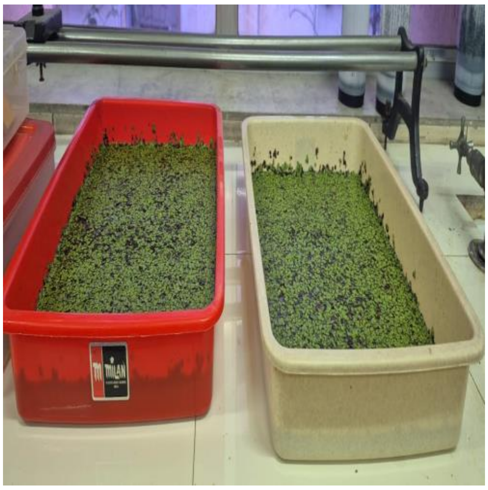

Figure C.4 (Rhizofiltration): Biological treatment tank utilizing Lemna minor (Duckweed) for the active absorption of nitrates, phosphates, and heavy metals.

C.3 Process Validation & Testing

Figure C.5 (Chemical Coagulation): Sedimentation stage using Iron (III) Chloride ($FeCl_3$) to precipitate suspended solid impurities from the raw greywater[5]

Figure C.6 (Quality Verification): Real-time validation of water quality parameters (TDS and Electrical Conductivity) using calibrated digital meters to ensure safety.