

## Summary: Multi-Stage Water Purification System

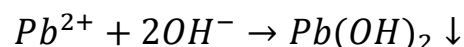
This research presents a **Smart Water Monitoring and Purification Device** developed to detect and purify **five major water quality parameters** — **pH, Lead (Pb), Mercury (Hg), Manganese (Mn), and Magnesium (Mg)** integrating **ESP32-S3 sensors** for real-time monitoring. The system employs a **three-stage purification process** combining oxidation, adsorption, ion exchange, and remineralization techniques.

### Stage 1: Oxidation for Manganese Removal

- **Purpose:**  
Removes dissolved manganese ( $Mn^{2+}$ ) responsible for black staining, metallic taste, and potential health effects.
- **Method:**
- **Aeration:**  
Uses dissolved oxygen to oxidize  $Mn^{2+} \rightarrow MnO_2$ .
- **Greensand Filtration:**  
Catalyzes oxidation using manganese-coated media.
- **Chemical Reaction:**  
$$3Mn^{2+} + 2KMnO_4 + 2H_2O \rightarrow 5MnO_2 \downarrow + 4H^+ + 2K^+$$
- **Outcome:**  
Insoluble  $MnO_2$  is filtered out; water aesthetics and safety improve.

### Stage 2: Heavy Metal Adsorption & Chemical Reduction

- **Purpose:**  
Eliminates toxic heavy metals—**Lead ( $Pb^{2+}$ )** and **Mercury ( $Hg^{2+}$ )**—via adsorption and redox processes.
- **Filtration Media:**  
**Activated Carbon + KDF (Kinetic Degradation Fluxion)** media.
- **Mechanisms:**
- **Mercury:**  
$$Hg^{2+} + 2e^- \rightarrow Hg^0;$$
  
then adsorbed on carbon.
- **Lead:**



or complexation with carbon surfaces.

- **Result:**

Heavy metals are converted into insoluble or adsorbed forms, safely removed during backwashing.

### Stage 3: pH Balancing and Remineralization

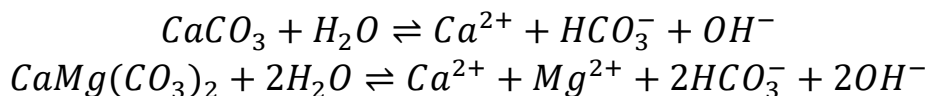
- **Purpose:**

Adjusts pH and reintroduces essential minerals ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) for healthy, balanced drinking water.

- **Media:**

**Limestone ( $\text{CaCO}_3$ ) or Dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ).**

- **Reactions:**



- **Effect:**

Water becomes slightly alkaline and mineral-rich, improving taste and stability.

### Pollutant Summary & Chemical Reactions

Parameter	Source	Removal Method	Reaction	Output	Example Sensor (Pakistan)
<b>pH (<math>\text{H}^+</math>)</b>	Acidic/basic imbalance	Neutralization	$\text{H}_2\text{CO}_3 + \text{Ca}(\text{OH})_2 \rightarrow \text{CaCO}_3\downarrow + 2\text{H}_2\text{O}$	Neutral water	DFRobot pH Sensor V2
<b>Lead (<math>\text{Pb}^{2+}</math>)</b>	Pipes, effluent	Precipitation/Adsorption	$\text{Pb}^{2+} + 2\text{OH}^- \rightarrow \text{Pb}(\text{OH})_2\downarrow$	Lead sludge	DFRobot $\text{Pb}^{2+}$ ISE
<b>Mercury (<math>\text{Hg}^{2+}</math>)</b>	Industrial waste	Sulfide precipitation	$\text{Hg}^{2+} + \text{S}^{2-} \rightarrow \text{HgS}\downarrow$	HgS precipitate	Mercury ISE Probe
<b>Manganese (<math>\text{Mn}^{2+}</math>)</b>	Groundwater, mining	Oxidation + Filtration	$3\text{Mn}^{2+} + 2\text{KMnO}_4 + 2\text{H}_2\text{O} \rightarrow 5\text{MnO}_2\downarrow + 4\text{H}^+ + 2\text{K}^+$	$\text{MnO}_2$ solid	DFRobot $\text{Mn}^{2+}$ ISE

Parameter	Source	Removal Method	Reaction	Output	Example Sensor (Pakistan)
Magnesium (Mg <sup>2+</sup> )	Natural minerals	Lime softening	$\text{Mg}(\text{HCO}_3)_2 + 2\text{Ca}(\text{OH})_2 \rightarrow 2\text{CaCO}_3\downarrow + \text{Mg}(\text{OH})_2\downarrow + 2\text{H}_2\text{O}$	Mg precipitate	DFRobot Mg <sup>2+</sup> ISE

### Smart Monitoring Integration

- **Microcontroller:**  
ESP32-S3 for IoT connectivity.
- **Features:**
  - Real-time water quality sensing (pH, Pb, Hg, Mn, Mg).
  - Automated chemical dosing via pH feedback.
  - Multi-stage purification and cloud-based monitoring.

### Merits

- High accuracy with modular sensor integration.
- Effective multi-contaminant purification.
- Environmentally sustainable via remineralization.
- Scalable for R&D and municipal applications in Pakistan.

### Demerits

- Periodic maintenance of filters and media required.
- Sensor calibration and cost constraints for multi-ion systems.
- Complex design increases initial setup expense.

### Conclusion

This **Multi-Stage Smart Water Purification System** represents a forward-looking R&D solution for **Pakistan’s water quality challenges**, merging **IoT-based real-time sensing** with **traditional purification principles** (oxidation, adsorption,

filtration, and remineralization). It ensures safe, mineral-balanced, and environmentally compliant drinking water aligned with **EPA and WHO standards**.