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:**

$$Pb^{2+} + 2OH^- \rightarrow Pb(OH)_2 \downarrow$$

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 (Ca^{2+}, Mg^{2+}) for healthy, balanced drinking water.
- **Media:**
  Limestone ($CaCO_3$) or **Dolomite ($CaMg(CO_3)_2$)**.
- **Reactions:**

$$CaCO_3 + H_2O \rightleftharpoons Ca^{2+} + HCO_3^- + OH^-$$

$$CaMg(CO_3)_2 + 2H_2O \rightleftharpoons Ca^{2+} + Mg^{2+} + 2HCO_3^- + 2OH^-$$

- **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)**
pH (H^+)	Acidic/basic imbalance	Neutralization	$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3\downarrow + 2H_2O$	Neutral water	DFRobot pH Sensor V2
Lead (Pb^{2+})	Pipes, effluent	Precipitation/Adsorption	$Pb^{2+} + 2OH^- \rightarrow Pb(OH)_2\downarrow$	Lead sludge	DFRobot Pb^{2+} ISE
Mercury (Hg^{2+})	Industrial waste	Sulfide precipitation	$Hg^{2+} + S^{2-} \rightarrow HgS\downarrow$	HgS precipitate	Mercury ISE Probe
Manganese (Mn^{2+})	Groundwater, mining	Oxidation + Filtration	$3Mn^{2+} + 2KMnO_4 + 2H_2O \rightarrow 5MnO_2\downarrow + 4H^+ + 2K^+$	MnO_2 solid	DFRobot Mn^{2+} ISE

Parameter	Source	Removal Method	Reaction	Output	Example Sensor (Pakistan)
Magnesium (Mg^{2+})	Natural minerals	Lime softening	$Mg(HCO_3)_2 + 2Ca(OH)_2 \rightarrow 2CaCO_3\downarrow + Mg(OH)_2\downarrow + 2H_2O$	Mg precipitate	DFRobot Mg^{2+} 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**.