Basics of Heavy Metal Pollution:

Heavy metal pollution in the environment is a result of both natural and anthropogenic processes. Naturally occurring heavy metals such as lead (Pb), arsenic (As), cadmium (Cd), copper (Cu), mercury (Hg), chromium (Cr), zinc (Zn), nickel (Ni), and others are found in mineral deposits and soils as insoluble compounds that are largely inaccessible to living organisms. These metals are typically bound tightly to soil particles or minerals, limiting their availability for uptake by plants and animals. Natural geological processes such as volcanic eruptions, weathering of rocks, erosion, and sedimentation contribute to the redistribution of these metals into the environment. (Source)

Table 1.

HM concentrations in igneous and sedimentary rocks, measured in parts per million (ppm).

HMs	Basaltic Igneous	Granite Igneous	Clays and Shales	Black Shales	Sandstone
Cu	48–240	5–140	18–180	34–1500	2–41
Zn	2–18	6–30	16–50	7–150	<1–31
Pb	30–160	4–30	18–120	20–200	–
Cd	0.006–0.6	0.003–0.18	0–11	<0.3–8.4	–

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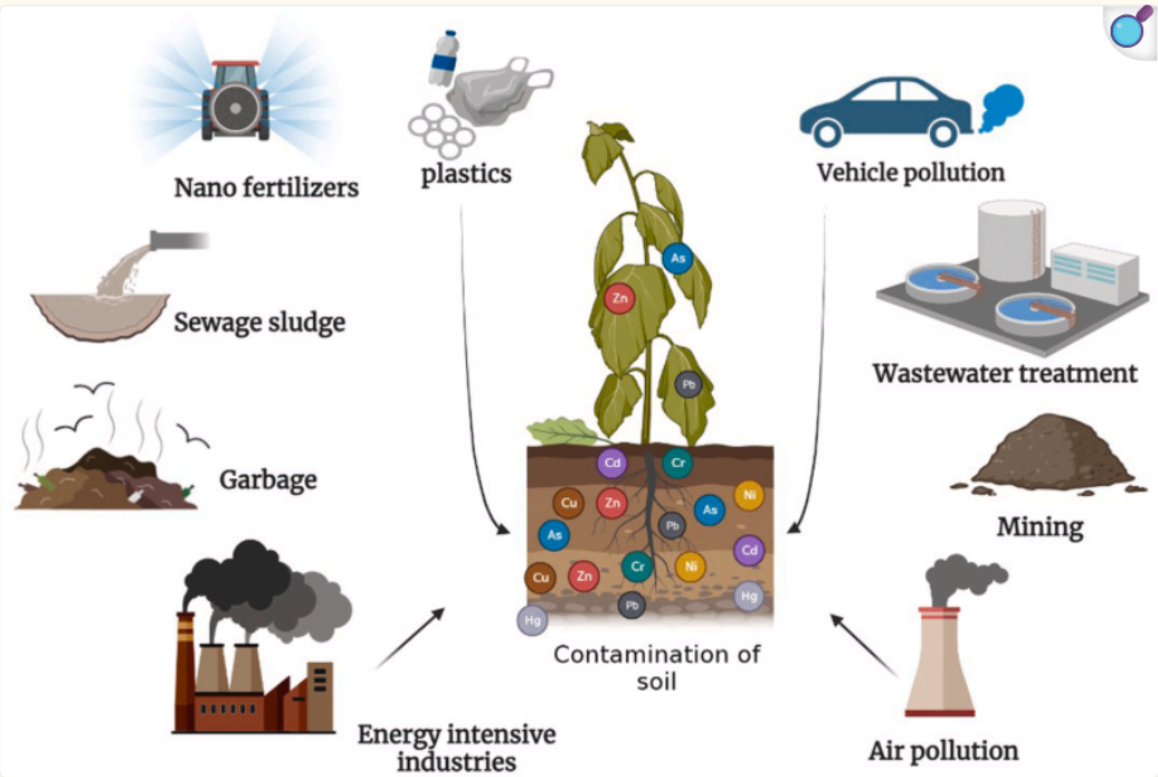
However, anthropogenic activities have drastically increased the bioavailability and environmental concentrations of heavy metals. Sources include mining, smelting, industrial manufacturing, use of pesticides and fertilizers in agriculture, combustion of fossil fuels, waste disposal, battery production, and electroplating industries. Unlike natural forms, heavy metals from human activities often exist in soluble and reactive forms, which are readily absorbed by plants, animals, and humans, leading to higher risks of environmental contamination and health hazards. Areas near mining sites, industrial complexes, and urban centers typically exhibit elevated heavy metal levels due to atmospheric deposition, wastewater discharge, and soil contamination from solid waste. (Source)

Fig. 1.



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Different sources of HMs (vehicle, mining, garbage, sewage, plastics, Nano-fertilizer, wastewater).

Industrial Sources of HM (Source):

Heavy metals are released into the environment as a result of rising human activity, such as industrial advancements. Eventually, these contaminants build up in the soil, especially in areas that are rapidly industrializing [36,37].

Some industrial sources of heavy metals are.

Lead

Combustion of fossil fuels, paints and pigments; application of lead in gasoline, fertilizers, solid waste, incineration of industrial waste, explosive, ceramics and dishware, solid waste combustion, paints and pigments, industrial dust and fumes, manufacturing of lead-acid batteries, pesticides, mining and metallurgy, some types of PVC, urban runoff [38].

Nickel

Industrial dust, electroplating, production of iron and steel, food processing industries, chemical industries, incineration of waste, fertilizers, industrial aerosols, mining and metallurgy, battery, and combustion of coal [39].

Chromium

Textile industry, metal plating, paints and pigments, rubber, photography, tanning, chemical industry, leather industry, industrial dust and fumes, fertilizers, mining and metallurgy [40,41].

Mercury

industrial wastewater, fossil fuel combustion, fluorescent bulbs, chlor-alkali, scientific instruments, production of chemicals, mercury arc lamps, industrial dust and fumes, incineration of municipal wastes, pesticides, fertilizers, solid waste combustion, smelting and metallurgy, electrical switches, explosive, rubber and plastics, mercury products (mercury amalgam, thermometers, batteries), cellulose, mining [42].

Copper

Textile industry, plating, paints and pigments, rayon, mining and metallurgy, pesticides, mining and metallurgy, explosives, electrical and electronics waste [43].

Arsenic

Industrial dust and waste, smelting of gold, lead, mining, smelting, medicinal, textile, pharmaceutical, wastewater, metal hardening, pesticides, paints, copper and nickel, production of steel and iron, phosphate fertilizers, combustion of fossil fuels [42].

Cadmium

PVC products, phosphate fertilizer, color pigments, electronics, industrial and incineration dust and fumes, pesticides, pigments and paints, batteries, mining and metallurgy and wastewater [44].

Zinc

Metal waste, fertilizers, electroplating, plating iron and steel, galvanization, mining and metallurgy.

Metals are non-biodegradable and cannot be decomposed (17,18). However, living organisms can detoxicate metals through various mechanisms, such as sequestering them within proteins or deposition in insoluble granules. These detoxification methods allow for the excretion of the metals in the organism's feces or prolonged storage. Upon swallowing or inhalation of HMs into our bodies, they accumulate over time in our system leading to their classification as being dangerous. This bioaccumulation leads to physiological and biological complications. (Figure 3) demonstrates a schematic representation of HM pollution in aquatic ecosystems. Heavy metals persist in the environment because they do not degrade, accumulate over time, and can biomagnify through the food chain, affecting soil, water, air, and biota. For example, mercury vapor emitted in the atmosphere can deposit into aquatic ecosystems, where it converts to toxic methylmercury accumulating in fish consumed by humans. These pollutants are non-biodegradable and can alter the biogeochemical cycles, posing serious ecological and human health challenges. (Source)

Environmental Impact and Health Risk:
Mercury (Hg)

Mercury exists in elemental, inorganic, and organic forms, with organic methylmercury being the most toxic. It is absorbed through inhalation and ingestion, accumulating mainly in the brain and kidneys. Toxicity leads to neurotoxicity, renal damage, gastrointestinal problems, and hepatotoxicity. Animal studies show cognitive impairment, kidney injury, and liver damage, often influenced by sex hormones. Human exposure, notably via contaminated fish, can cause severe neurological and developmental disorders such as Minamata disease.

Lead (Pb)

Lead is a widespread pollutant absorbed mainly through the respiratory and digestive tracts. It disrupts neurological, respiratory, urinary, and cardiovascular systems mainly via oxidative stress and inflammation. Animal studies indicate liver, kidney, and brain damage, while human studies link lead exposure to anemia, immunomodulation, respiratory issues, and cardiovascular diseases. Lead interferes with enzymes critical for heme synthesis, causing anemia. Occupational exposures raise risks of respiratory symptoms and systemic toxicity.

Chromium (Cr)

Chromium exists mainly as trivalent chromium (essential in trace amounts) and hexavalent chromium (Cr VI), a known occupational carcinogen. Cr (VI) exposure induces oxidative stress, DNA damage, and tumors through generation of reactive oxygen species. Animal studies demonstrate carcinogenicity in multiple organs, including the liver, kidney, and lungs. Human studies confirm increased cancer risks (lung, bladder, liver) associated with Cr (VI) exposure and DNA/chromatin damage mechanisms.

Cadmium (Cd)

Cadmium is released mainly by industrial pollution and accumulates in food and tobacco. It concentrates in liver and kidneys, causing nephrotoxicity, hepatotoxicity, osteoporosis, and cardiovascular diseases. Animal research shows altered zinc and copper metabolism, kidney injury, apoptosis, and disruption of cellular functions. Humans exposed to cadmium suffer from kidney dysfunction, bone fractures, cancer risks, and cardiovascular effects, with biomarkers such as urinary cadmium and beta 2-microglobulin used for monitoring.

Arsenic (As)

Arsenic, a notorious poison, occurs in inorganic and organic forms, with inorganic As being more toxic. It disrupts mitochondrial function and enzyme activities, generating oxidative stress leading to neurological, hepatic, skin, and reproductive toxicities. Animal studies reveal neurodegeneration and apoptosis. Human data link As exposure to DNA damage, adverse pregnancy outcomes, skin disorders, and cancers. Inflammation and oxidative stress are key pathogenic mechanisms.

General Overview

Heavy metals induce toxicity largely by binding to sulfhydryl groups of enzymes and generating reactive oxygen species (ROS). This leads to oxidative stress, enzyme inhibition, cellular damage, metabolic abnormalities, immune dysregulation, and increased cancer risk. Environmental contamination by these metals is widespread, even in remote regions like Mount Everest. Regulatory limits on daily intake and environmental presence are recommended to reduce human health risks and monitor exposure, especially via food, water, occupational, and medicinal product sources.

(Source)

Summary of the Research Paper

Background

- Soil contamination by heavy metals is a significant environmental problem, especially near industrial and mining areas.
- Major sources include industrial emissions, fossil fuel combustion, and mining activities.
- Heavy metal pollution threatens agriculture, ecological safety, and human health.

Study Area and Data Collection

- The study area is a 1113.83 km² industrial and mining zone southeast of Tianjin, China.
- Soil samples (85 points) were collected using a systematic random grid method.
- Heavy metals analyzed: arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), and mercury (Hg).
- Concentrations were measured via atomic emission and fluorescence spectrometry.

Methodology

Cluster Analysis

- Hierarchical cluster analysis was conducted to group heavy metals based on possible sources.
- Heavy metal concentrations were standardized using Z-scores.
- Euclidean distances were used to assess similarity among metals.

$$Sik = (I_{Ni}, R_{Ii})$$

$$Sjk = (I_{Nj}, R_{Ij})$$

$$d_{ij} = \sqrt{(I_{Ni} - I_{Nj})^2 + (RI_i - RI_j)^2}$$

Where dij is the Euclidean distance between sample points i and j, and K is a variable.

Geo-Accumulation Index (I_geo)

- Used to assess contamination levels of individual heavy metals, reducing interference from natural background variations.

$$I_{geo} = log_2 \frac{C_n}{1.5B_n}$$

Where Cn is the measured concentration of heavy metal n in soil, and Bn is the geochemical background value of metal n.

Class	I_{geo} range	Contamination Level
0	≤ 0	Uncontaminated
1	0 – 1	Uncontaminated to moderately contaminated
2	1 – 2	Moderately contaminated
3	2 – 3	Moderately to heavily contaminated
4	3 – 4	Heavily contaminated
5	4 – 5	Heavily to extremely contaminated
6	> 5	Extremely contaminated

Table 1.

Geochemical background value (mg/kg).

Metals	As	Cd	Cr	Cu	Pb	Ni	Zn	Hg
Values	12.70	0.10	67.30	22.50	21.00	31.00	65.40	0.02

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$$I_N = \sqrt{\frac{{I_{\text{geo,max}}}^2 + {I_{\text{geo,ave}}}^2}{2}}$$

where $I_{\text{geo,max}}$ is the maximum geo-accumulation index and $I_{\text{geo,ave}}$ is the average geo-accumulation index for all metals at the sampling point (Formula 3).

- Classification of I_N contamination level:

Class	I_N range	Contamination Level
0	0 – 0.5	Uncontaminated
1	0.5 – 1	Uncontaminated to moderately contaminated
2	1 – 2	Moderately contaminated
3	2 – 3	Moderately to heavily contaminated
4	3 – 4	Heavily contaminated
5	4 – 5	Heavily to extremely contaminated
6	> 5	Extremely contaminated

There are more methods of analysis , it would simply be more efficient to read the research paper.
Research paper based in Bangladesh.

2.Datasets and research
heavy metals in ground water
Summary:

- **Monitoring:** Central Ground Water Board (CGWB) monitors groundwater quality across India. Its studies show contaminants like arsenic, lead, cadmium, and chromium often exceed **BIS permissible limits** in isolated pockets.
- **Extent of Issue:**
  - **154 districts in 21 States/UTs** report arsenic contamination.

    - **92 districts in 14 States** report lead contamination.
    - **24 districts in 9 States** report cadmium contamination.
    - **29 districts in 10 States** report chromium contamination.
- **Punjab Example (Malwa Belt):** Arsenic in Mansa, Faridkot, Sangrur; Lead in Bathinda, Ferozepur, Muktsar; Cadmium in Ludhiana, Patiala, Sangrur; Chromium in Bathinda, Mansa, Sangrur; Uranium in 9 districts.
- **Habitations Affected:** As of Dec 2021, **36,873 rural habitations** in India had water quality issues (iron, arsenic, fluoride, salinity, nitrate, heavy metals).
- **Government Action:**
    - **Jal Jeevan Mission (JJM):** Ensuring safe tap water to rural households, prioritizing contaminated habitations.
    - **Jal Shakti Abhiyan (2019 & 2021 – Catch the Rain):** Groundwater recharge and harvesting to improve water quality.
    - **National Water Quality Sub-Mission (2017):** Focused on arsenic/fluoride removal, now under JJM.
    - **AMRUT (Urban Mission):** Allows states to take up projects for safe water supply in urban areas.
    - **National Aquifer Mapping Programme (NAQUIM):** Identifying safe aquifers and providing technical solutions to states.
    - **Regulation:** 2020 guidelines issued for groundwater extraction and pollution control.

https://www.sciencedirect.com/science/article/abs/pii/S2212095522001511

Summary:

- **Study Area**:
  Delhi's Yamuna River floodplains – highly urbanized and industrialized, with intensive agriculture and untreated waste discharge. Groundwater here is the main drinking source for many communities.
- **Sampling & Methodology**:
    - **64 samples** collected (32 pre-monsoon, 32 post-monsoon).

    - Pollution measured using indices:
        - **Heavy Metal Pollution Index (HPI)**
        - **Degree of Contamination (Cd)**
        - **Health Risk Assessment** (non-carcinogenic + carcinogenic risks).
    - **Principal Component Analysis (PCA)** used to identify sources.
- **Key Metals Detected (order of abundance)**:
  Fe > Mn > Zn > B > As > Ni > Pb
- **Pollution Status**:
    - **HPI results**: 53% (pre-monsoon) and 44% (post-monsoon) samples in *high-risk* zone (HPI >100).
    - **Degree of Contamination (Cd)**: ~55% samples were *highly polluted*.
    - Indicates widespread and **seasonally persistent contamination**.
- **Health Risk Findings**:
    - **Hazard Index (HI)** >1 in many samples → significant *non-carcinogenic* risk.
    - **Carcinogenic risk (CR)** also above safety thresholds.
    - **Children** face *higher health risks* (both cancerous & non-cancerous) compared to adults due to lower body weight and higher exposure per unit weight.
    - Long-term exposure linked to **chronic illnesses** (liver damage, kidney failure, nervous system disorders, cardiovascular issues, reproductive problems, and cancers).
- **Pollution Sources**:
    - **Natural (non-anthropogenic)**: As, Fe, Mn, Zn (likely from geology, weathering, aquifer sediments).
    - **Mixed (natural + human activities)**: B, Ni, Pb (industrial waste, urban runoff, agriculture, poor irrigation practices).
- **Conclusion**:

    - Delhi's Yamuna floodplain groundwater is **severely polluted with heavy metals**.
    - The contamination is a **serious health threat**, especially to children.
    - Calls for urgent **environmental monitoring, treatment measures, and stricter regulation** of effluent discharge.

https://iwaponline.com/wpt/article/19/2/419/100253/GIS-based-assessment-of-groundwater-vulnerability

Summary:

🔑 Study Objective

The research evaluates the **extent of heavy metal contamination in groundwater** of Aligarh city, India, caused largely by **industrial effluents**. It uses **GIS-based mapping** and water quality indices—**Heavy Metal Pollution Index (HPI)** and **Contamination Index (CDx)**—to assess pollution and health risks.

📍 Study Area

- Location: Aligarh, Uttar Pradesh, between the Ganga and Yamuna rivers.
- Highly industrialized (lock, textile, electroplating, leather industries).
- Poor drainage system → wastewater stagnation increases risk of groundwater infiltration.

🧪 Methodology

- **Samples collected**:
    - 17 groundwater samples (handpumps, tube wells).
    - 20 industrial effluent samples.
- Heavy metals tested: **Ni, Cu, Zn, Fe, Mn, Cr, Pb**.

- Analysis done using **Atomic Absorption Spectrometer**.
- GIS mapping (ArcGIS + IDW interpolation) used to show spatial spread of contamination.
- Results compared with **WHO, BIS, and EPA drinking water standards**.

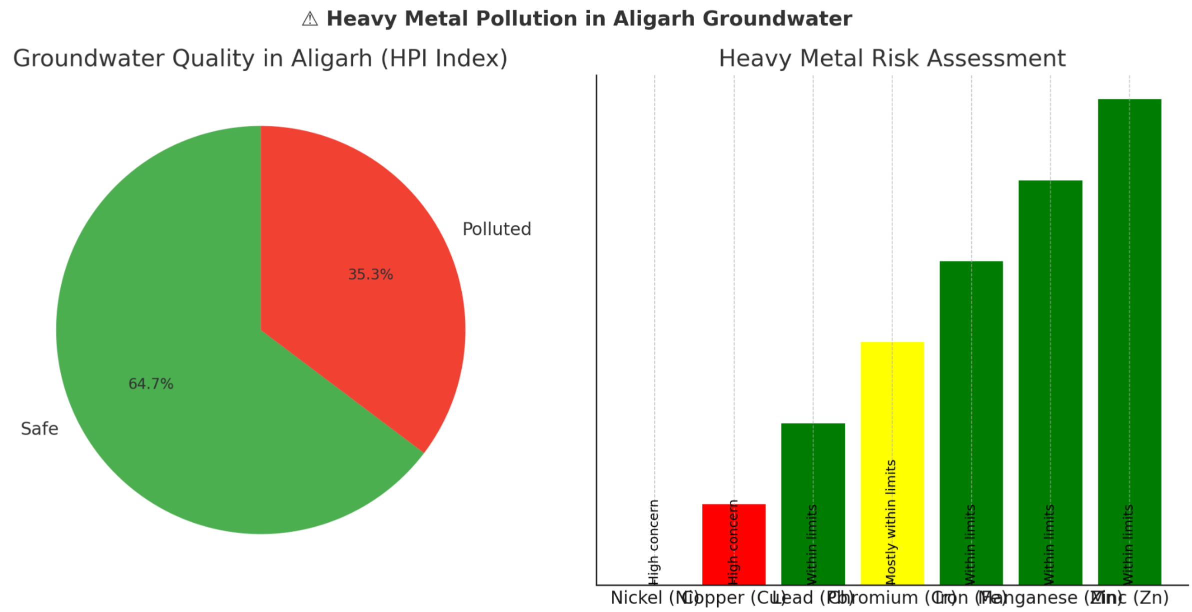
📊 Key Findings

1. **Industrial Effluents** contained very high concentrations of metals:
    - Cr: 18.3 mg/l
    - Ni: 13.3 mg/l
    - Fe: 6.3 mg/l
    - Cu: 1.99 mg/l
    - Pb: 1.2 mg/l
      (all well above permissible limits).
2. **Groundwater** showed lower but concerning traces:
    - Ni (avg 1.87 mg/l), Cu (avg 0.98 mg/l) often exceeded safe limits.
    - Pb, Cr, Fe, Mn, Zn generally within limits, but hotspots exist.
3. **Index Results**:
    - **HPI**: 64.7% of locations safe (<100), 35.3% polluted (>100).
    - **CDx**:
        - 23.5% = pure
        - 17.6% = slightly affected
        - 11.7% = moderately affected
        - 11.7% = severely affected
        - 29.4% = extensively polluted

4. **Health Risk**: Linked with kidney stones, skin diseases, liver and kidney issues reported in local hospitals.

📌 Conclusion

- Groundwater in Aligarh is **significantly impacted by industrial effluents**, particularly by **nickel and copper**.
- **GIS mapping** effectively highlighted vulnerable hotspots.
- Urgent need for **centralized effluent treatment plants (CETPs)**, strict regulation, and continuous monitoring to safeguard drinking water quality.



[Water Quality Degradation Due to Heavy Metal Contamination: Health Impacts and Eco-Friendly Approaches for Heavy Metal Remediation - PMC]()

Water quality issues:

- Heavy metal contamination is a serious concern.
- Sources: industrial effluents, agricultural runoff, domestic waste, and unsanitary landfills.

Common toxic metals found:

- Chromium (Cr), Cadmium (Cd), Lead (Pb), Arsenic (As), Mercury (Hg), Nickel (Ni), Copper (Cu).

Health hazards of heavy metals:

- Liver and kidney damage
- Respiratory and reproductive issues
- Neurological disorders
- Cancer risks
- Bioaccumulation in food chains and drinking water sources

Limitations of traditional removal methods:

- Reverse osmosis, precipitation, adsorption, membrane filtration
- Costly, energy-intensive
- Create secondary pollutants
- Not sustainable in the long run

Eco-friendly alternatives (biological methods):

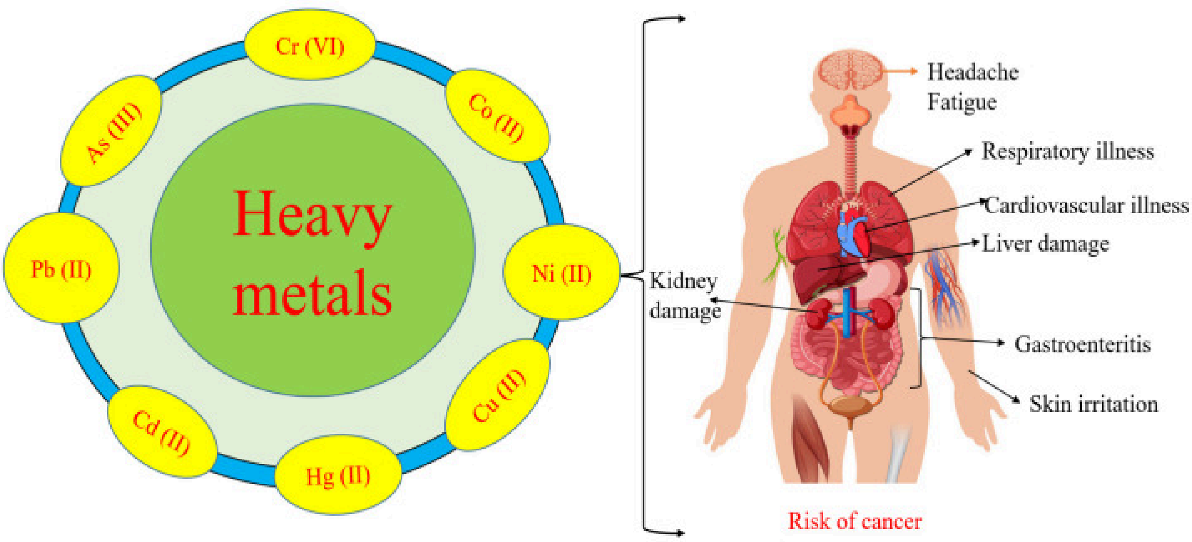
- **Biosorption** – using agricultural waste (banana peel, rice husk, etc.)
- **Bioaccumulation** – microbes absorb and store metals
- **Bioreduction** – microbes convert metals to less harmful forms
- **Phytoremediation** – plants absorb and immobilize metals
- **Mycoremediation** – fungi used for metal removal
- Algae and bacteria (e.g., *Pseudomonas*, *Bacillus*) show high efficiency

Advantages of biological methods:

- Low cost
- Environmentally friendly
- Effective at even low metal concentrations
- Can be improved by modifying biosorbents to increase efficiency

Conclusion:

- Heavy metal pollution is a growing urban and industrial issue.
- Eco-friendly remediation is urgently needed.
- Strict water quality monitoring and regulations must be enforced.
- Biological approaches offer sustainable, long-term solutions.



3. Data Reviewer and Validator

1. **Introduction to the Role**

A Data Reviewer & Validator ensures that the data used in the Heavy Metal Pollution Indices application is accurate, scientifically sound, and aligned with global standards. This role focuses on verifying every dataset, calculation, and system output so that decision-makers and the public can trust the application's results. Inaccurate data or flawed calculations can lead to false conclusions about water quality and environmental safety, which makes validation a critical step in environmental software development.

2. Key Responsibilities

1. **Cross-check AI-Implemented Formulas:**
    - Review algorithms and formulas used to calculate indices like HPI (Heavy Metal Pollution Index), HEI (Heavy Metal Evaluation Index), and MI (Metal Index).
    - Ensure formula accuracy by comparing them with published scientific literature and environmental standards.
2. **Validate App Outputs Against Literature:**
    - Take sample datasets from trusted government or research sources.
    - Perform manual calculations in tools like Excel.
    - Compare these results with application outputs to verify correctness.
3. **Bug and Logic Quality Assurance (QA):**
    - Identify logical errors, incorrect standards, or miscalculations in the application.
    - Provide structured feedback to developers for error correction.

3.1 Heavy Metal Pollution Index (HPI)

$$HPI = \frac{\sum(Q_i \times W_i)}{\sum W_i}$$

Where:

- $$Q_i = \frac{M_i - I_i}{S_i - I_i} \times 100$$
- Mi: Measured concentration of metal i
- Ii: Ideal concentration (often 0 for heavy metals)
- Si: Standard permissible limit of metal i
- Wi : Weight assigned to each metal based on toxicity

Interpretation: Higher HPI values indicate more severe pollution.

3.2 Heavy Metal Evaluation Index (HEI)

$$HEI = \sum \left(\frac{M_i}{H_{MAC_i}} \right)$$

Where Hmaci is the maximum allowable concentration for each heavy metal.

Interpretation: HEI simplifies overall water quality evaluation.

3.3 Metal Index (MI)

$$MI = \sum \left(\frac{C_i}{MAC_i} \right)$$

Where Ci is the measured concentration and MACi is the permissible limit.

Interpretation: If MI > 1, the water is considered unsafe.

4. WHO and Indian BIS Standards

Metal	WHO Limit (mg/L)	BIS Limit (mg/L)	Health Impact
Lead (Pb)	0.01	0.01	Brain damage, developmental delays
Mercury (Hg)	0.006	0.001	Neurological issues, kidney damage
Cadmium (Cd)	0.003	0.003	Kidney damage, bone weakness
Arsenic (As)	0.01	0.01	Cancer, skin lesions
Chromium (Cr)	0.05	0.05	Respiratory issues, cancer

Nickel (Ni)	0.07	0.02	Lung damage, skin irritation
Copper (Cu)	2.0	0.05	Liver and kidney problems
Zinc (Zn)	3.0	5.0	Stomach distress at high levels

https://applications.emro.who.int/imemrf/J_Ayub_Med_Coll_Abbotabad_Pak/J_Ayub_Med_Coll_Abbotabad_Pak_2001_13_4_12_15.pdf

5. Validation Workflow

Step	Action
1. Collect Data	Download heavy metal concentration data from CPCB or research papers.
2. Record Standards	Use WHO/BIS safe limits as reference.
3. Manual Calculations	Calculate HPI, HEI, MI in Excel or manually for selected samples.
4. Compare Results	Match manual results with app's calculations.
5. Identify Bugs	Highlight errors in formulas, data interpretation, or coding.
6. Report Findings	Document errors and provide recommendations for fixes.

6. Example Validation

If Lead (Pb) concentration is 0.02 mg/L, permissible limit is 0.01 mg/L:

$$Q_{Pb} = \left(\frac{0.02 - 0}{0.01}\right) \times 100 = 200$$

If $W_{Pb} = 1$:

$$HPI = \frac{200 \times 1}{1} = 200$$

Interpretation: HPI is very high, indicating unsafe water. The app should flag this water sample as unsafe.

7.Common Bug / Logic Types

- **Formula implementation errors** (wrong formula, missing parentheses, incorrect weights).

- **Wrong standard usage** (using WHO limit where BIS should be used, or unit mismatch e.g., µg/L vs mg/L).
- **Data type issues** (strings instead of numbers, rounding/truncation errors).
- **Missing / null handling** (app crashes or gives incorrect index when a metal value is missing).
- **Edge-case misbehavior** (zero, negative, extremely high values).
- **Aggregation/weighting errors** (weights not normalized or omitted).
- **Unit conversion errors** (µg/L ↔ mg/L).
- **Rounding/precision errors** (small differences in floating point).
- **UI vs backend mismatch** (app displays one value but backend calculates another).

QA Process — Step by Step

1. **Detect**
    - Use sample datasets from CPCB or papers and app-run outputs.
    - Apply quick sanity checks (e.g., if all metals are 0 → indices must be 0 or safe).
2. **Reproduce**
    - Re-run the same input in the app and reproduce the failure consistently.
    - Record exact input, timestamp, app version, and UI steps.
3. **Isolate**
    - Test each formula independently (HPI, HEI, MI).
    - Test one metal at a time (set others to 0) to find which metal causes mismatch.
4. **Document**
    - Fill a concise **Bug Report** (template below).
    - Attach screenshots, sample CSV/Excel, manual calculation, and app output.
5. **Report**

- Send to developers with severity and reproduction steps. Use version control tags if available.

6. **Verify Fix**
   - Once fixed, re-run the original dataset and regression test suite (see checklist).
   - Mark "fixed" only if the app output matches manual calculations and no new issues introduced.

7. **Regression Testing**
   - Re-run a set of previously passed tests to ensure no new bugs.

Investigating the impacts of heavy metal(loid)s on ecology and human health

The potential ecological risk index (RI) for heavy metals, as introduced by Hakanson in 1980, is a technique employed to evaluate the potential risk associated with the presence of heavy metals in a specific ecosystem. This index takes into account factors such as the concentrations, types, sensitivity, toxicity, and background levels of the heavy metals, as noted by Xie et al.

$$\mathrm{RI} = \sum E_{\mathrm{r}}^{i} = T_{\mathrm{r}}^{i} \times \left\{ \frac{C_{\mathrm{ave}}^{i}}{C_{\mathrm{bg}}^{i}} \right\}$$

where E_r indicates a substance's potential ecological risk factor;
T_r illustrates the given heavy metal toxic response factor;
C^{i}_{ave} stands for the background values of each heavy metal;
RI is the overall contamination's potential ecological risk.;
RI has four risk levels: low (below 30), moderate (30–60), considerable (60–120), and very high (over 120).

The consumption of drinking water contaminated with toxic metals increases the potential for both non-carcinogenic and carcinogenic diseases in humans. The USEPA, (2004) established a health risk assessment approach to determine the non-cancer human health risks from heavy metal elements in groundwater and surface water through ingestion, inhalation, and skin contact. The primary risk stemmed from direct water consumption and absorption through the skin. This method calculates the quantity of pollutants consumed by humans using the chronic daily intake (CDI) approach, which expresses the daily dose of pollutants in kilograms consumed through ingestion (CDI ingestion) and dermal absorption (CDI dermal).

$$\mathrm{CDI}_{\mathrm{oral}} = \frac{C_{\mathrm{ave}} \times \mathrm{IR} \times \mathrm{EF}}{\mathrm{BW} \times \mathrm{AT}} \times \mathrm{ED}$$

$$\mathrm{CDI}_{\mathrm{dermal}} = \frac{C_{\mathrm{ave}} \times \mathrm{ET} \times \mathrm{EF} \times K_p \times \mathrm{SA} \times \mathrm{CF}}{\mathrm{BW} \times \mathrm{AT}} \times \mathrm{ED}$$

CDI represents the chronic daily intake (mg/kg/day);
C_{ave} depicts the average concentration of each heavy metal (mg/L)
IR stands for the intake rate (adult: 2.2 L day^{-1}; child: 1.8 L day^{-1});
EF denotes the exposure frequency (adult and child: 350 days/year);
ED signifies the exposure duration (adult: 70 years; child: 6 years);
ET represents the exposure time (adult: 0.58 h day^{-1}; child:1h day^{-1});
K_p is the permeability coefficient (cm/h).
SA depicts the skin area (adult: 18,000 ; child: 6600 cm^2).
BW is the body weight (adult: 70 kg; child: 15 kg);
CF is the unit conversion factor (1×10^{-3} L cm^{-3});
AT indicates the average time for carcinogenic risks (adult: 25,550 days; child: 2190 days)

In the second step, we calculated the hazard quotient (HQ) by dividing the chronic daily intake (CDI) by the reference dose (RFD) for both oral and dermal exposure

$$\mathrm{HQ}_{\mathrm{dermal/oral}} = \frac{\mathrm{CDI}_{\mathrm{dermal}}/\mathrm{CDI}_{\mathrm{oral}}}{\mathrm{RfD}_{\mathrm{dermal}}/\mathrm{RfD}_{\mathrm{oral}}}$$

$$\mathrm{RfD}_{\mathrm{dermal}} = \mathrm{RfD}_{\mathrm{oral}} \times \mathrm{ABS}$$

In the final step, the overall potential non-carcinogenic risks were assessed by calculating the hazard index (HI) using

$$\mathrm{HI} = \mathrm{HQ}_{\mathrm{oral}} + \mathrm{HQ}_{\mathrm{dermal}}$$

Toxic metals that have a hazard index (HI) or hazard quotient (HQ) of greater than 1 may pose negative impacts on human health, while those with a HI or HQ of less than 1 are considered to have no adverse effects.

Following Li and Zhang's methodology (Li & Zhang, 2010), the degree of carcinogenic risk (CR) was ascertained using Eq. 10. The resulting value indicates the probability of developing cancer throughout one's lifetime due to exposure to carcinogens. Normally, the acceptable or permissible range for such risks lies between 1×10^{-6} and 1×10^{-4}.

$$\mathrm{CR} = \mathrm{CDI} \times \mathrm{CSF}$$

where CSF is the cancer slope factor

RESULTS AND DISCUSSIONS:

Heavy metal concentrations in surface water

The present study investigated the distributions of eight heavy metals at seven representative sites, as illustrated in Table 1. Specifically, the concentrations of the following heavy metals—As, Cr, Cu, Fe, Mn, Ni, Pb, and Zn—were determined and averaged over two distinct periods: April–September and October–March. During April–September, the average concentrations of As, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were 1.29, 1.43, 4.03, 520.63, 53.02, 2.70, 1.31, and 15.00 µg/L, respectively. The mean concentrations of these heavy metals were ranked in descending order: Fe > Mn > Zn > Cu > Ni > Cr > Pb > As. Conversely, during October–March, the average concentrations of As, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were 1.44, 1.36, 3.69, 403.36, 39.71, 2.51, 1.27, and 15.59 µg/L, respectively. The mean concentrations of these determined heavy metals were ranked in descending order: Fe > Mn > Zn > Cu > Ni > As > Cr > Pb. Importantly, the mean concentrations of Fe and Mn exceeded the standard limits established by both the EU Directive and WHO in 2017.

Table1.

The parameters for the computation of HQ, HI, RI and CR

HM	As	Cr	Cu	Fe	Mn	Ni	Pb	Zn
RfD Oral(mg/kg/day)	0.0003	0.003	0.04	0.7	0.024	0.02	0.0014	0.3
ABS	1	0.025	0.3	0.2	0.04	0.04	0.3	0.2
Rfd Dermal(mg/kg/day)	0.0003	0.000075	0.012	0.14	0.00096	0.0008	0.00042	0.06
CSFing mg/kg/day	1.5	0.5					0.5	
CSFderm	50	500					500	
K_p	0.001	0.002	0.001	0.001	0.001	0.0002	0.0001	0.0006
Background (µg/g)	10	30	30	15,000	500	20	20	100
T_r	10	2	5	1	1	5	5	1

In terms of health risk assessment, non-carcinogenic health risk was evaluated using the hazard quotient (HQ) and hazard index (HI) for both oral and dermal exposures. The results indicated no significant risk for both adults and children ($HI < 1$ and $HQ < 1$). However, arsenic posed a carcinogenic health risk to children through oral exposure ($CR > 1 \times 10^{-4}$), and chromium presented a carcinogenic health risk for both adults and children through dermal exposure in both periods ($CR > 1 \times 10^{-4}$). Notably, the data suggested that children were more susceptible to lead-induced cancer compared to adults, as their oral cancer risk (CR) exceeded the threshold value of ($CR > 1 \times 10^{-4}$).