Volume-10 Issue 03, March -2026 ISSN: 2456-9348
Impact Factor: 8.232

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

HEAVY METAL CONTAMINATION (PB, CD, AS, AND CR) IN GROUNDWATER FROM NATURAL AND ANTHROPOGENIC SOURCES: A SYSTEMATIC REVIEW COMPARING CONCENTRATIONS WITH WORLD HEALTH ORGANIZATION WATER QUALITY STANDARD

Jannene L. Alam[1]
Fiona Eunice R. Gasis[1]
Crisha Marie P. Salamat[1]
Gecelene C. Estorico[1,2]
Civil and Allied Department; Environmental Science and Chemical Technology Department
[1]Technological University of the Philippines - Taguig Metro Manila 1630, Philippines
[2]De La Salle University - Dasmariñas, Cavite, DBB-B, 4115 West Ave., Dasmariñas

ABSTRACT
Groundwater is a critical freshwater resource for domestic, agricultural, and industrial use; however, it is increasingly threatened by heavy metal contamination. This systematic review evaluates contamination by Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr) in groundwater from both natural and anthropogenic sources and compares reported concentrations with World Health Organization (WHO) drinking water standards. Using the PRISMA framework, peer-reviewed studies published between 2016 and 2026 were screened, with ten studies meeting the inclusion criteria. The results show distinct spatial and metal-specific contamination patterns. High contributions were observed in Bangladesh for Pb (~47%), Zimbabwe for Cd (~44%), India for As (~84%), and the Philippines for Cr (~65%). These patterns reflect the influence of industrial activities, mining, waste mismanagement, and geogenic processes. Arsenic and Chromium are strongly associated with carcinogenic risks, while Lead and Cadmium primarily contribute to neurological and renal health effects. Most study sites reported concentrations exceeding WHO limits, with Hazard Quotient (HQ > 1) and Incremental Lifetime Cancer Risk (ILCR > 10^{-4}) indicating significant health risks. The findings highlight substantial spatial variability driven by geological conditions and human activities. Continuous monitoring, improved regulatory enforcement, and targeted remediation strategies are essential to protect public health and ensure sustainable groundwater management.

Keywords:
Risk, Toxicity, Carcinogenic Heavy Metals, Safety Standards

INTRODUCTION

Groundwater remains a cornerstone of freshwater supply for domestic consumption, agricultural irrigation, and industrial processes globally, supporting billions yet increasingly imperiled by pervasive heavy metal contamination from Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr). These contaminants infiltrate aquifers through natural pathways like geological weathering and volcanic activity, as well as anthropogenic drivers such as mining operations, electroplating industries, pesticide applications, and untreated effluents (RSC Publishing, 2014; Jaishankar et al., 2014). The non-biodegradable nature, propensity for bioaccumulation in food chains, and toxicity at microgram-per-liter levels trigger multifaceted health threats, including neurodevelopmental deficits, nephrotoxicity, hepatotoxicity, dermatological lesions, reproductive impairments, and carcinogenesis via reactive oxygen species generation, protein denaturation, and genotoxic DNA adducts (Tchounwou et al., 2012; Cleveland Clinic, 2023).

In vulnerable developing regions like India and the Philippines—where groundwater accounts for over 80% of rural drinking water supplies amid sparse regulatory oversight and monitoring infrastructure—proximal contamination hotspots near industrial corridors, smelters, and rice paddies frequently surpass World Health Organization (WHO) drinking water guidelines (Pb ≤ 0.01 mg/L, Cd ≤ 0.003 mg/L, As ≤ 0.01 mg/L, Cr ≤ 0.05

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

mg/L total Cr). This discrepancy amplifies non-carcinogenic hazards (e.g., hazard index >1.0) and carcinogenic potentials (e.g., lifetime excess cancer risk $>1 \times 10^{-4}$), disproportionately burdening children, pregnant women, and low-income communities through chronic ingestion (WHO, 2017; Briffa et al., 2020). Such exposures not only strain public health systems but also undermine ecological integrity and socioeconomic sustainability, necessitating integrated risk frameworks that bridge geochemical profiling with toxicological endpoints.

This systematic review addresses these gaps by systematically reviewing published studies on heavy metal contamination in groundwater from Natural and Anthropogenic Sources worldwide. It rigorously benchmarks findings against WHO standards, computes source apportionment via multivariate statistics, evaluates human health risks through hazard quotients and cancer slope factors, and delineates ecological implications for aquatic biota. Ultimately, the study furnishes evidence-based recommendations for remediation technologies (e.g., phytoremediation, nanotechnology), policy reforms, and monitoring protocols to fortify groundwater resilience, avert health crises, and align with Sustainable Development Goal 6 on clean water access (RSC Publishing, 2014; Jaishankar et al., 2014).

OBJECTIVES

Main Objective:

- To systematically review published studies on heavy metal contamination in groundwater from Natural and Anthropogenic Sources and evaluate reported concentrations against the water quality standards of the World Health Organization.

Specific Objectives:

1. To compile and analyze published studies reporting concentrations of heavy metals (Pb, Cd, As, and Cr) in groundwater sources such as wells, ponds, and aquifers from Natural and Anthropogenic Sources.
2. To compare the reported heavy metal concentrations in groundwater with the water quality standards established by the World Health Organization.
3. To identify patterns and trends in heavy metal contamination in groundwater associated with Natural and Anthropogenic Activities based on the findings of previous studies.

METHODOLOGY

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor, transparency, and reproducibility. The protocol guided the identification, screening, eligibility assessment, and inclusion of peer-reviewed literature addressing heavy metal contamination in groundwater, with a specific focus on Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr) from natural and anthropogenic sources.

Data Sources

A comprehensive and systematic search of published literature was conducted to identify relevant studies on heavy metal contamination in groundwater from natural and anthropogenic sources. Academic databases including Google Scholar, ScienceDirect, PubMed, Web of Science, and SpringerLink were searched to ensure broad coverage of peer-reviewed scientific literature. All retrieved records were assessed using the PRISMA framework to maintain methodological consistency, ensure transparency in the article selection process, and facilitate reproducibility of the review findings.

Literature Search

A comprehensive literature search was performed across five academic databases: Google Scholar, ScienceDirect, PubMed, Web of Science, and SpringerLink. To ensure broad coverage and minimize the risk of missing relevant studies, a combination of keywords and Boolean operators (AND, OR) was employed. The search strategy was structured around two thematic keyword sets. The first set targeted heavy metals and groundwater, incorporating terms such as "Heavy Metal Contamination," "Groundwater Pollution," "Lead," "Pb," "Cadmium," "Cd," "Arsenic," "As," "Chromium," "Cr," "Aquifer," "Well water," "Tube well," and "Drinking water." The second set focused on contamination sources and included terms such as "Industrial Area," "Mining," "Smelting," "Landfill," "Agricultural runoff," "Geogenic," and "anthropogenic." The search was restricted to peer-reviewed journal

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

articles and scientific studies published in English between 2016 and 2026. Supplementary reference materials, including books, technical reports, and government publications such as World Health Organization or Department of Environment and Natural Resources guidelines, were consulted for conceptual background but were not included in the final synthesis unless they met the predefined inclusion criteria.

Screening and Selection Process

All retrieved records were imported into a reference management system for deduplication. The screening process followed the PRISMA framework, proceeding through three stages: title and abstract screening, full-text review, and final inclusion. During the initial screening, studies were assessed based on the titles, authors, publication metadata, and source journals to eliminate duplicate records. Irrelevant studies were subsequently excluded, and the remaining articles were subjected to full-text review to determine alignment with the study objectives.

Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: (1) original research articles or peer-reviewed scientific papers published between 2016 and 2026; (2) focused specifically on groundwater samples, including wells, boreholes, tube wells, and aquifers; (3) collected from areas within five kilometers or as defined by the study of active or historical industrial sites, landfills, mining areas, or regions with documented natural heavy metal occurrence; (4) reported quantitative concentrations of at least one of the target heavy metals: Lead, Cadmium, Arsenic, or Chromium; and (5) provided sufficient methodological detail, including sampling procedures and analytical techniques. Studies were excluded if they: (1) were review articles, conference abstracts, editorials, or opinion pieces without original data; (2) did not report quantitative heavy metal concentrations; (3) focused on surface water, sediment, or biota without groundwater analysis; (4) were published before 2015; (5) were not available in English or lacked full-text access; or (6) lacked sufficient methodological detail to allow for quality assessment or data extraction.

Search Results

A total of 92 studies were initially identified through the database search. Following the removal of 12 duplicate records, 70 studies proceeded to title and abstract screening. During this stage, 35 studies were excluded based on irrelevance to the research objectives, including studies focused on surface water, sediment, or biological matrices without groundwater analysis, as well as those addressing heavy metals not among the four target analytes. The remaining 35 studies underwent full-text eligibility assessment. Of these, 25 were excluded due to insufficient quantitative data, lack of methodological detail, absence of comparison with World Health Organization standards, or unavailability of full-text versions. Ultimately, 10 studies met all inclusion criteria and were included in the qualitative synthesis. The identification, screening, eligibility assessment, and final inclusion process are summarized in the PRISMA flow diagram (Figure 1)

ISSN: 2456-9348
Impact Factor: 8.232

iJETRM
International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

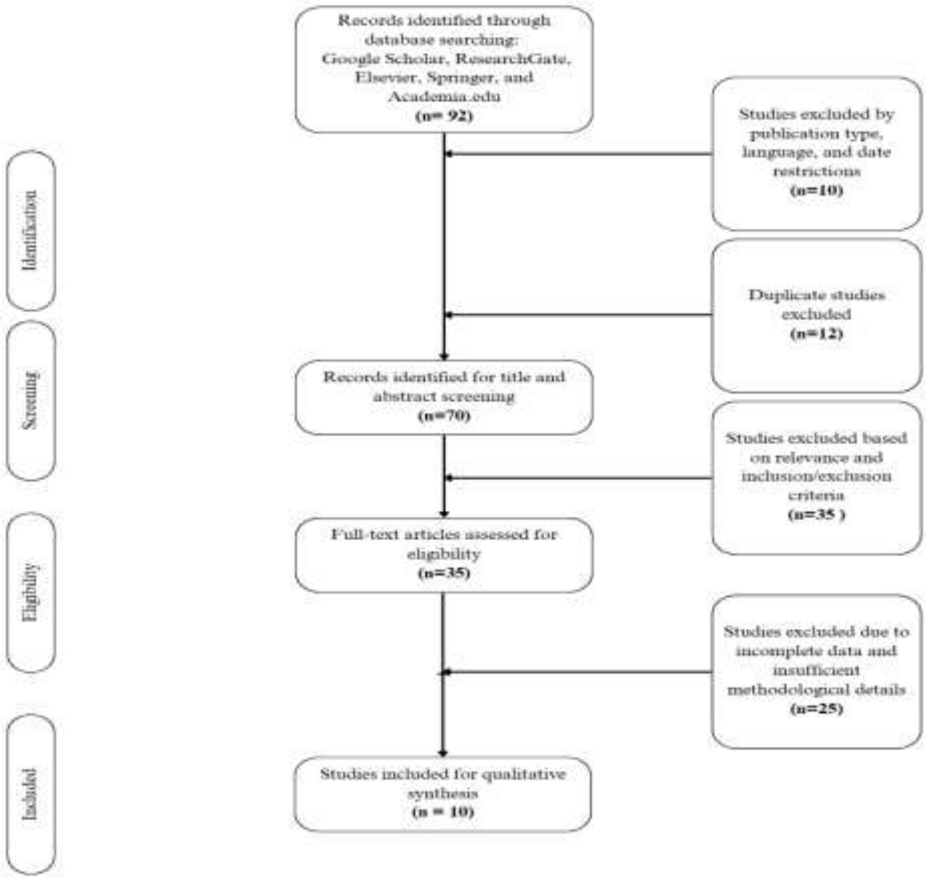

Figure 1. Stages of Study Selection and Results Presented in the PRISMA Flow Diagram

Data Extraction

Data extraction was performed using a pre-designed and standardized form to ensure consistency and completeness across all included studies. For each article, bibliographic information including authors, year of publication, country of origin, and journal source was recorded. Details regarding study design, sampling locations, and groundwater sources were documented. Key parameters related to heavy metal analysis were extracted, including the types of water sources sampled, number of sampling sites, analytical methods used such as atomic absorption spectrometry or inductively coupled plasma mass spectrometry, detection limits, and quality assurance procedures. Reported concentrations of Lead, Cadmium, Arsenic, and Chromium were extracted as mean values, ranges, and measures of variability such as standard deviation or standard error, along with sample sizes and statistical analyses used. Comparisons with World Health Organization drinking water quality standards were recorded where available. Two reviewers independently performed data extraction for all included studies, and inconsistencies were resolved through discussion, with arbitration by a third reviewer when necessary. All extracted data were compiled in a master spreadsheet and cross-checked against the full-text articles. When essential numerical values or methodological details were missing or unclear, attempts to contact corresponding authors were made and documented in an extraction log.

Data Synthesis and Risk Assessment

To facilitate a standardized comparison across the included studies, three analytical metrics were employed to evaluate the magnitude and potential health implications of heavy metal contamination in groundwater. The first metric, percentage of samples exceeding the WHO limit, was calculated to determine the proportion of groundwater samples in each study that surpassed the World Health Organization drinking water guideline values for Lead (10 µg/L), Cadmium (3 µg/L), Arsenic (10 µg/L), and Chromium (50 µg/L). This metric was expressed as:

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

$$Exceedance(\%) = \frac{Number\ of\ sample\ exceeding\ WHO\ limit}{Total\ number\ of\ samples} \times 100$$

The second metric, Hazard Quotient (HQ), was used to assess the non-carcinogenic health risk associated with ingestion of heavy metal-contaminated groundwater. The HQ was calculated using the following formula:

$$HQ = \frac{CDI}{RfD}$$

Where Chronic Daily Intake (CDI) was derived as:

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

Where:
C= concentration (mg/L)
IR= ingestion rate (L/day)
EF= exposure frequency (days/year)
ED= exposure duration (years)
BW= body weight (kg)
AT= averaging time (days)
RfD= reference dose (mg/kg/day)

Interpretation:
HQ < 1 → No significant risk
HQ > 1 → Potential non-carcinogenic risk

In these equations, C represents the concentration of the heavy metal in water (mg/L), IR is the ingestion rate (L/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the body weight (kg), AT is the averaging time (days), and RfD is the reference dose (mg/kg/day). An HQ value greater than 1 indicates a potential non-carcinogenic health risk.

The third metric, Incremental Lifetime Cancer Risk (ILCR), was employed to estimate the carcinogenic risk associated with lifetime exposure to heavy metals classified as known or probable human carcinogens, specifically Arsenic and Chromium. The ILCR was calculated using the formula:

$$ILCR = CDI \times CSF$$

Where:
CSF= Cancer Slope Factor

Interpretation:
$10^{-6}$to 10^{-4} → Acceptable risk
10^{-4} → Significant cancer risk

where CSF is the cancer slope factor $(\mathrm{mg/kg/day})^{-1}$. The ILCR value represents the probability of developing cancer over a lifetime due to exposure to the contaminant. According to the United States Environmental Protection Agency, an ILCR between 1×10^{-6} and 1×10^{-4} is generally considered acceptable or tolerable, while values exceeding 1×10^{-4} indicate a significant carcinogenic risk

Risk of Bias Assessment

The risk of bias for all included studies was evaluated using a modified assessment tool adapted for environmental contamination research. The assessment examined whether sampling locations and groundwater sources were clearly defined and justified, whether sample collection and preservation methods followed established protocols,

iJETRM
International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

and whether analytical techniques were validated and appropriate for the target metals. The evaluation also considered the adequacy of quality control measures, including the use of certified reference materials, reagent blanks, and replicate analyses. Reporting bias was assessed based on the completeness of outcome reporting, transparency in handling non-detectable values, and whether all measured metals were consistently reported. Statistical and analytical rigor were assessed by documenting sample sizes, replication, and measures of variability. Each study was graded with low, moderate, or high risk of bias, with justification provided for each rating. Two reviewers independently conducted the assessment, and disagreements were resolved through discussion or by involving a third reviewer when necessary. Common issues across the body of evidence included insufficient reporting of quality control measures, limited replication, and variability in analytical detection limits. These bias assessments informed how individual findings were weighted in the narrative synthesis and contributed to the overall interpretation of heavy metal concentrations relative to World Health Organization standards.

RESULTS AND DISCUSSION

Risk Level in each Heavy Metal in relation to the WHO Water Quality Standards

The risk levels of selected heavy metals such as Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr) in groundwater are assessed by comparing reported concentrations from both natural and anthropogenic sources with guideline values established by the World Health Organization. These guideline values are designed to protect human health from both acute and chronic exposure to contaminants in drinking water. Heavy metals are persistent environmental pollutants characterized by toxicity, non-biodegradability, and bioaccumulative nature. They can enter groundwater systems through natural processes such as rock weathering and mineral dissolution, as well as anthropogenic activities including industrial discharge, mining, agricultural runoff, and improper waste disposal (Mititelu, 2025). Once present in groundwater, these metals may remain for long periods and pose long-term health risks through continuous exposure. Risk levels are primarily determined by comparing measured concentrations with WHO guideline values and evaluating the toxicological properties of each metal. Even low concentrations may be hazardous due to bioaccumulation and prolonged exposure, which can result in severe health effects such as neurological damage, kidney dysfunction, immune system disruption, and cancer (Mititelu, 2025).

Table 1. WHO Permissible Limits for Selected Heavy Metals

Heavy Metal	WHO Guideline Value (μg/L)	Risk Interpretation
Lead (Pb)	10 μg/L	Highly toxic even at low levels
Cadmium (Cd)	3 μg/L	Very high toxicity, accumulative
Arsenic (As)	10 μg/L	Carcinogenic, critical pollutant
Chromium (Cr)	50 μg/L	Toxic, carcinogenic (Cr^{6+})

Lead (Pb) is considered a high-risk contaminant due to its strong neurotoxic effects, particularly in children, where it can impair cognitive development and cause long-term neurological damage (Mititelu, 2025). Its ability to accumulate in bones and tissues further increases its risk even at low concentrations. Cadmium (Cd) poses significant health risks because of its long biological half-life and tendency to accumulate in the kidneys, leading to renal dysfunction and skeletal damage. It is also classified as a carcinogenic element and is commonly introduced into groundwater through industrial and agricultural activities (Yirenkyi-Fianko & Ottou, 2024). Arsenic (As) is widely recognized as one of the most critical groundwater contaminants due to its carcinogenic nature and widespread occurrence in both natural geological formations and industrial sources. Chronic exposure has been linked to skin lesions, cardiovascular diseases, and various cancers, even at relatively low concentrations (Mititelu, 2025). Chromium (Cr), particularly in its hexavalent form (Cr^{6+}), is highly toxic and carcinogenic. It is commonly associated with industrial pollution, especially from metal processing and ferrochrome industries, and can cause organ damage and cancer upon long-term exposure (Patra, 2025). Overall, the risk posed by these heavy metals is influenced not only by the concentration in groundwater but also by exposure duration, chemical speciation, and population vulnerability. Studies have shown that exceedance of WHO limits particularly for Pb and Cr can significantly compromise groundwater safety and pose serious public health threats (WHO, 2017).

Causes of Heavy Metal Contamination

Groundwater contamination by heavy metals such as Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr) results from both anthropogenic activities and natural geogenic processes. Evidence from the reviewed studies indicates that human activities are the primary drivers of elevated contamination levels in high-risk areas. Industrial operations including manufacturing, mining, metal processing, and wastewater discharge introduce significant amounts of heavy metals into the environment (Singh et al., 2023). These contaminants infiltrate soil layers and migrate into aquifers, increasing concentrations in nearby groundwater sources. This pattern is consistently observed in industrial regions where contamination levels frequently exceed recommended limits (Kapoor et al., 2024).

Agricultural activities also contribute to groundwater contamination through the prolonged use of fertilizers, pesticides, and other agrochemicals containing trace metals. Over time, these substances accumulate in the soil and are transported into groundwater through leaching, particularly during rainfall or irrigation. Improper waste management practices such as unlined landfills and uncontrolled waste disposal further intensify contamination by producing leachate that carries heavy metals into subsurface water systems. Natural processes including the weathering of rocks and dissolution of metal-bearing minerals also contribute to the presence of heavy metals in groundwater. These geogenic sources are especially relevant in areas with specific geological characteristics such as alluvial sediments or ultramafic formations. While natural processes explain background concentrations, significantly elevated levels are more often associated with anthropogenic inputs (Kumar & Maurya, 2025).

Health Effects of Heavy Metal Contamination

Heavy metals like Pb, Cd, As, and Cr in groundwater exert toxicity through bioaccumulation and multi-organ damage when exceeding WHO limits (Pb: 0.01 mg/L, Cd: 0.003 mg/L, As: 0.01 mg/L, Cr: 0.05 mg/L), primarily via ingestion from contaminated drinking water. These contaminants induce oxidative stress, protein/DNA binding, and enzyme disruption, with effects varying dose, duration, age, and nutrition; children are most vulnerable due to higher absorption and developing systems.

Lead (Pb)

Pb interferes with calcium signaling, crossing the blood-brain barrier to cause neurotoxicity via excitotoxicity and synaptic pruning disruption, yielding IQ reductions (2-4 points per 10 µg/dL blood Pb rise), learning disabilities, hyperactivity, and behavioral issues in children. In adults, it promotes hypertension (via renal Na^{+} retention), anemia (heme inhibition), kidney impairment, reproductive toxicity (sperm damage), and immune dysfunction; severe cases involve seizures or coma. Even low chronic exposure links to hearing loss, shorter stature, and lifelong cognitive deficits. (WHO 2024; USEPA 2026; Siame 2025)

Cadmium (Cd)

Cd mimics essential metals, binding metallothionein for renal accumulation, causing tubular proteinuria, glucosuria (Fanconi syndrome), osteomalacia ("Itai-Itai" disease), and osteoporosis via Ca/Zn displacement. It elevates lung cancer (OR=1.3-3.1), glucose dysregulation (diabetes), heart failure, and cerebral infarcts through ROS and inflammation. Acute symptoms include nausea, vomiting, diarrhea, cramps, and salivation; chronic risks amplify in smokers or via food chains (Mahajan 2022; WQA 2015).

Arsenic (As)

Arsenic undergoes hepatic methylation (inefficiently), generating ROS/DMA for DNA hypermethylation and adducts, driving skin hyperkeratosis/discoloration, peripheral neuropathy (numbness, pain), GI distress (nausea, diarrhea), and cancers (skin, lung, bladder; SIR up to 150/100,000). Vascular effects include hypertension, Blackfoot disease, and diabetes (via insulin signaling); detection challenges mimic common illnesses (WHO 2022; Shankar 2014).

Chromium (Cr)

Cr (VI) penetrates cells, reducing to Cr (III) with ROS bursts, Cr-DNA adducts, and metastasis promotion, classifying it as a carcinogen (lung, GI). Oral exposure causes GI ulcers/bleeding, dermatitis, nasal perforation, hematological changes, and renal toxicity; Greek/Indian studies link drinking water Cr (VI) (~20 mg/L) to elevated GI/dermatological complaints. All routes disrupt cell adhesion and induce oxidative damage (Shin 2023).

Environmental Impacts of Heavy Metal Contamination

Heavy metal contamination in groundwater poses significant and long-lasting environmental consequences due to the persistence, toxicity, and bioaccumulative nature of these elements. When contaminated groundwater is used for irrigation, heavy metals such as Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr) can

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

accumulate in soils and be taken up by crops. This process facilitates the entry of toxic metals into the food chain, where concentrations may increase through bioaccumulation and biomagnification, ultimately affecting both terrestrial organisms and human populations (Ali et al., 2019).

Groundwater also serves as a hydrological link to surface water systems. Through processes such as baseflow and seepage, contaminated groundwater can transport heavy metals into rivers, lakes, and wetlands. This introduces pollutants into aquatic environments, where these metals can accumulate in sediments and aquatic organisms, leading to toxicity, impaired reproduction, and reduced biodiversity (Tchounwou et al., 2019). Aquatic species, particularly benthic organisms, are especially vulnerable due to the direct and prolonged exposure to contaminated sediments. The environmental persistence of heavy metals further intensifies impact. Unlike many organic pollutants, heavy metals are non-biodegradable and can remain in soils and sediments for extended periods, often decades. The accumulation can alter soil physicochemical properties, disrupt microbial communities, and interfere with essential ecological processes such as nutrient cycling and organic matter decomposition (Briffa et al., 2020). These changes can reduce soil fertility, impair plant growth, and ultimately decrease agricultural productivity. Overall, the environmental impacts of heavy metal contamination extend beyond localized groundwater pollution, affecting interconnected terrestrial and aquatic ecosystems. These effects underscore the importance of continuous monitoring and effective management strategies to mitigate heavy metal contamination from both natural and anthropogenic sources (Briffa et al., 2020).

Table 2. Causes of heavy metal contamination and Health Effects, with the environmental impacts that occur

Heavy Metal	City, Country	Causes	Health Effects	Environmental Impacts	Authors/date
Pb, Cd, As, Cr	Rupnagar district, Punjab, India	Natural (geogenic) processes and anthropogenic activities such as industrial discharge, agricultural inputs, and improper waste disposal	Potential non-carcinogenic and carcinogenic risks due to chronic exposure; hazard index and cancer risk values indicate possible health concerns, especially in children	Water quality deterioration, unsafe untreated and pre-treated water, accumulation of heavy metals in drinking water systems	Kapoor et al. (2024)
Pb, Cd, As, Cr	Maharashtra, India	Contamination comes from both natural processes (like erosion and weathering) and human activities (such as mining, industry, agriculture, and settlements).	Arsenic contributes the most health risk from ingestion of water. Consumers reported frequent loose stools, abdominal pain, and stomach discomfort.	Contamination of both groundwater and surface water systems, bioaccumulation of heavy metals, degradation of water quality, transfer of pollutants across interconnected water systems	Mawari et al. (2022)
Pb, Cd, As, Cr	Mirzapur, Uttar Pradesh, India	Natural and anthropogenic activities on water resources	Children are most at risk from groundwater contamination. Fe and Cd exceed safe limits, causing health concerns, while As and Cd pose high cancer risks. Pb and Cr are low but toxic, and Zn is safe. Monsoon reduces exposure but risks remain.	High ERI indicates environmental stress such as water scarcity, soil degradation, loss of vegetation, and increased temperatures, which can harm ecosystems and reduce land productivity.	Tripathi et al. (2025)

iJETRM
International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

Pb, Cd, As, Cr	Madhya Pradesh, India	Coal mining activities, geogenic (natural rock sources), vehicular emissions, leaching into groundwater	Non-carcinogenic health risks (especially in children), neurological disorders, kidney damage, and potential cancer risks (As, Cr in some locations); ingestion is the main exposure pathway	Groundwater contamination, reduced drinking water quality, seasonal variation in metal concentration (higher during pre-monsoon), long-term risk to water resources and ecosystem health	Tiwari et al. (2025)
As, Cr	Puerto Princesa City, Philippines	Abandoned mercury mining activities (Palawan Quicksilver Mines Inc.), residual mine wastes, natural geology (cinnabar deposits)	Potential health risks from Cr exceeding drinking water standards; long-term exposure may affect kidneys, nervous system, and overall human health	Groundwater contamination in boreholes, localized pollution near pit lake, but limited mercury mobility; no mixing between groundwater and surface water observed	Samaniego et al. (2020)
Pb, Cd, As, Cr	Lantawan, Philippines	Possible sources include geogenic processes, agricultural inputs (fertilizers, pesticides), and anthropogenic activities; however, results suggest minimal industrial contamination	Potential risks include cancer (As, Cr), kidney damage (Cd), neurological effects (Pb, Hg), and organ damage with long-term exposure; microbial contamination poses additional health risks such as waterborne diseases	Groundwater generally chemically safe but vulnerable to contamination; presence of pollutants (including bacteria) indicates risk to water quality, ecosystem balance, and sustainability of water resources	Rodriquez et al. (2025)
Cd, Cr, Pb	Marinduque Island, Philippines	Past mining activities (copper mining from 1969–1997) including two major mining disasters (1993 and 1996); releases of metals from sediments; geological profile of the island (volcanic, igneous, and sedimentary rocks).	Potential for water quality-induced illnesses and waterborne-related diseases; consumption of contaminated groundwater poses health risks to communities relying on untreated groundwater for domestic supply.	Groundwater quality deteriorated, with 13 out of 35 sampling sites classified as severely polluted. Concentrations of Cr, Fe, Mn, Pb, and Zn exceeded the Philippine National Standards for Drinking Water (PNSDW) 2017. The highest pollution index was recorded in Brgy. Sumangga, with widespread severe pollution observed in the municipality of Torrijos.	De Jesus et al. (2021)
Pb, Cd	Bengal Coast Bay, Bangladesh	Industrial effluents (including from gas production plants), ship breaking yard	Potential for bioaccumulation in the food chain; consumption of contaminated seafood poses	High concentrations of metals exceeding international marine water quality standards.	Hasan et al. (2016)

iJETRM
International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

		activities, port operations, untreated urban waste, and riverine inflows.	a health risk to the local population.	Elevated contamination factor (CF) and pollution load index (PLI) values indicate significant metal pollution, threatening the aquatic ecosystem.	
As, Cd, Cr, Pb	Gaya, Bihar, India	Geogenic sources (rock weathering, mineral dissolution) and anthropogenic activities (overuse of fertilizers, industrial waste discharge).	Non-carcinogenic risks for 28% of adults and 44% of children; Arsenic and Nickel pose carcinogenic risks (36% and 46% of samples, respectively); children more vulnerable due to lower body weight.	Elevated heavy metal concentrations in groundwater; 56% of samples exceeded Al limit, 58% exceeded Fe limit, 20% exceeded Mn limit, 10% exceeded As limit; HPI values below 100 indicating low pollution; MI classified 92% of samples as very pure.	Kumar, S. & Maurya, N.S. (2025)
Pb, Cd, Cr	Bulawayo, Zimbabwe	Co-disposal of metallic and electronic wastes at unlined landfill; lack of membrane lining; inadequate leachate management; porous gravel soils allowing leachate seepage into shallow unconfined aquifer.	Pb and Cd in groundwater exceeded WHO drinking water standards; linked to neurological disorders, kidney and brain damage; children are particularly susceptible to Pb poisoning.	Groundwater contamination from Pb and Cd negatively correlated with distance from landfill; metals detected in landfill soil, leachate, and plants (pigweed, jimsonsweed), indicating mobility and bioavailability; water unsuitable for drinking.	Teta, C. & Hikwa, T.

The studies included in this review consistently identify both geogenic and anthropogenic sources as contributors to heavy metal contamination in water systems. Natural processes such as weathering and erosion are shown to contribute to baseline concentrations, while human activities including industrial discharge, mining operations, agricultural inputs, and improper waste disposal are associated with increased levels of Pb, Cd, As, and Cr. Across different study areas, higher concentrations are frequently reported in locations influenced by industrialization and mining, indicating a recurring pattern between human activities and declining water quality.

Findings from the reviewed studies indicate that chronic exposure to these heavy metals presents both non-carcinogenic and carcinogenic health risks. Arsenic is commonly identified as a major contributor to cancer risk through ingestion, while Cadmium and Lead are associated with kidney damage, neurological impairment, and developmental effects. Several studies emphasize that children are more vulnerable due to higher intake relative to body weight and ongoing physiological development. Reported health symptoms include gastrointestinal problems such as abdominal pain, diarrhea, and stomach discomfort, which are linked to contaminated water consumption. Ingestion is consistently identified as the primary exposure pathway, although dermal contact is also mentioned in some cases.

The environmental impacts described in the studies show patterns of water quality deterioration and ecosystem disruption associated with heavy metal contamination. Groundwater systems are frequently reported to contain elevated metal concentrations, reducing suitability for drinking and contributing to bioaccumulation in aquatic organisms. Some studies also report the movement of contaminants between surface water and groundwater systems, increasing the extent of environmental exposure. In addition, the presence of heavy metals is associated with soil degradation, vegetation loss, and reduced land productivity. Seasonal variations in concentration levels are also observed, with higher values reported during dry or pre monsoon periods, indicating the influence of hydrological conditions on contaminant distribution.

iJETRM
International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

Table 3. Heavy Metal concentration in groundwater in different Locations in relation to the Permissible limit according to WHO Water Quality Standards and the General Risk Level

Location (City, Country)	Heavy Metal Concentration (µg/L)				Risk Level
	Pb	**Cd**	**As**	**Cr**	
Rupnagar district, Punjab, India	1495	3	36	35	Very High Risk
Maharashtra, India	10	3	50	50	High Risk
Mirzapur, Uttar Pradesh, India	1.07	26.25	14.49	0.05	High Risk
Madhya Pradesh, India	11.65	3.842	7.95	41.29	High Risk
Puerto Princesa City, Philippines	0	0	8	175	High Risk
Lantawan, Philippines	10	2	5	30	Low / Acceptable Risk
Marinduque Island, Philippines	40.4	28.6	0	0.0504	Very High Risk
Bengal Coast Bay, Bangladesh	452	12	0	0	Very High Risk
Gaya, Bihar, India	1.71	0.09	2.98	3.94	Low Risk
Bulawayo, Zimbabwe	183	23	0	113	Very High Risk
WHO Standards (Permissible Limit)	10	50	10	3	~

[Low/Acceptable Risk – within limits; Moderate Risk – near or slightly exceeding limits; High Risk – clearly exceeding one or more limits; Very High Risk – far exceeding limits or confirmed by high ILCR (>10^{-4})]

Table 3 illustrates a clear spatial variability in heavy metal contamination and associated risk levels across different industrially influenced regions. Locations such as Rupnagar, Punjab (Pb: 1495 µg/L; As: 36 µg/L; Cr: 35 µg/L) and the Bengal Coast Bay, Bangladesh (Pb: 452 µg/L; Cd: 12 µg/L) are categorized as very high risk, reflecting concentrations that far exceed WHO drinking water standards and pointing to severe industrial discharge and agricultural runoff impacts. Similarly, Bulawayo, Zimbabwe (Pb: 183 µg/L; Cd: 23 µg/L; Cr: 113 µg/L) and Marinduque Island, Philippines (Cd: 28.6 µg/L) also fall into the very high-risk category, emphasizing the influence of mining and smelting activities. In contrast, sites such as Gaya, Bihar (Pb: 1.71 µg/L; Cd: 0.09 µg/L; As: 2.98 µg/L; Cr: 3.94 µg/L) and Lantawan, Philippines (Pb: 10 µg/L; Cd: 2 µg/L; As: 5 µg/L; Cr: 30 µg/L) are classified as low or acceptable risk, with concentrations generally within or near permissible limits, suggesting limited industrial impact or effective natural attenuation. Intermediate cases, including Maharashtra, Mirzapur, Madhya Pradesh, and Puerto Princesa City, are designated at high risk, where one or more metals clearly exceed WHO thresholds, indicating significant but not extreme contamination. Overall, the data reveal that industrially active regions tend to exhibit elevated heavy metal concentrations, often reaching hazardous levels, whereas less-affected areas show comparatively safer profiles. This pattern highlights the urgent need for targeted monitoring and remediation in high-risk zones to mitigate ecological and public health consequences.

iJETRM
International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

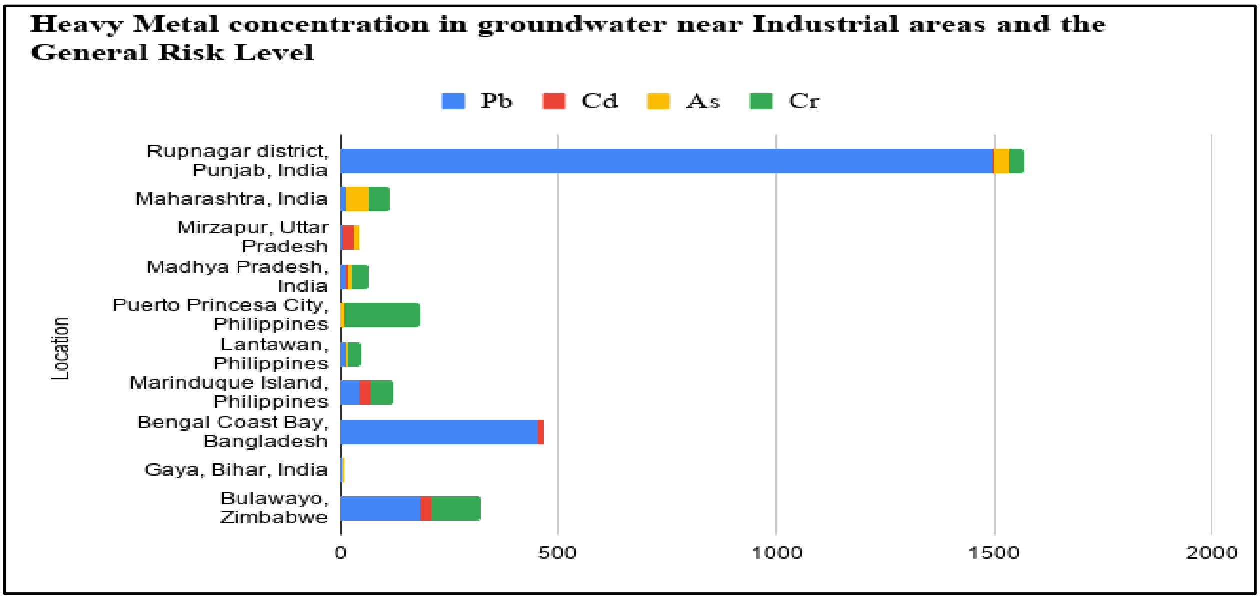

Figure 2. Heavy Metal concentration in groundwater near Industrial areas and the General Risk Level

Figure 2 provides a combined tabular and graphical representation of heavy metal concentrations in groundwater near industrial areas, alongside associated risk levels. The horizontal bar chart visually emphasizes the magnitude of contamination, with color-coded bars for Lead, Cadmium, Arsenic, and Chromium, making it easier to compare across locations. Sites such as Rupnagar, Punjab; the Bengal Coast Bay, Bangladesh; Marinduque Island; and Bulawayo stand out with extremely long bars for Pb, Cd, or Cr, corresponding to the classification as very high-risk zones. These locations clearly exceed WHO guideline values by wide margins, reflecting severe industrial pollution and inadequate mitigation measures. In contrast, Gaya and Lantawan show relatively short bars, indicating lower concentrations of metals and aligning with the low or acceptable risk status. Intermediate cases such as Maharashtra, Mirzapur, Madhya Pradesh, and Puerto Princesa City display moderate bar lengths, highlighting exceedances in one or more metals, and justifying high-risk categorization. Overall, the figure effectively illustrates the spatial variability of contamination, showing how certain industrially active regions face acute groundwater pollution, while others remain comparatively safer. This visual comparison underscores the urgent need for targeted interventions in high-risk areas to protect both ecological integrity and public health.

Table 4. Exceedance Factors and Quantitative Risk Indicators of Heavy Metal Contamination in Groundwater

Location	**Exceedance Factor (Detected Heavy Metal Conc. vs WHO)**				**% of Samples Exceeding WHO Limit**	**Hazard Quotient (HQ)***	**Incremental Lifetime Cancer Risk (ILCR)***
	Pb	**Cd**	**As**	**Cr**			
WHO Standard Limitsw	10 µg/L	3 µg/L	10 µg/L	50 µg/L			
Rupnagar district, Punjab, India	150×	1×	3.6×	<1×	100%	>1	$>10^{-4}$
Maharashtra, India	1×	1×	5×	1×	100%	>1	$>10^{-4}$
Mirzapur, Uttar Pradesh	<1×	9×	1.4×	<1×	100%	>1	$>10^{-4}$
Madhya Pradesh, India	1.1×	1.3×	<1×	<1×	100%	>1	$>10^{-4}$
Puerto Princesa City, Philippines	0	0	<1×	3.5×	100%	>1	$>10^{-4}$

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

Lantawan, Philippines	1×	<1×	<1×	<1×	~50%	≈1	N/A
Marinduque Island, Philippines	4×	9.5×	0	<1×	100%	>1	$>10^{-4}$
Bengal Coast Bay, Bangladesh	45×	4×	0	0	100%	>1	$>10^{-4}$
Gaya, Bihar, India	<1×	<1×	<1×	<1×	N/A	N/A	N/A
Bulawayo, Zimbabwe	18×	7.6×	0	2.3×	100%	>1	$>10^{-4}$

[N/A = Not Applicable as there are no risks or exceeding amounts versus the WHO Standards in the Heavy Metal Concentration]

The table provides a quantitative assessment of heavy metal contamination in groundwater across different industrially influenced regions, expressed through exceedance factors, percentage of samples surpassing WHO limits, hazard quotients (HQ), and incremental lifetime cancer risk (ILCR). The data clearly show that most locations (such as Rupnagar, Maharashtra, Mirzapur, Madhya Pradesh, Puerto Princesa, Marinduque, Bay of Bengal, and Bulawayo) record concentrations that exceed WHO standards by significant margins. For example, Rupnagar exhibits a Lead exceedance factor of 150× and Arsenic at 3.6×, with 100% of samples above permissible limits, resulting in HQ values greater than 1 and ILCR values above 10^{-4}, both indicative of severe health risks. Similarly, Bulawayo demonstrates Pb at 18× and Cd at 7.6× above limits, again translating into very high carcinogenic risk. Risk levels in Rupnagar vary due to the industrial discharge, agricultural inputs, and improper waste disposal that occurs in the area.

In contrast, Lantawan and Gaya present much lower contamination profiles. Lantawan shows borderline exceedances (Pb at 1×, Cr <1×) with approximately 50% of samples exceeding WHO limits, yielding HQ values around 1 and negligible ILCR, suggesting limited health concerns. Gaya, meanwhile, records all metals below WHO thresholds, with no exceedance, HQ <1, and ILCR not applicable, reflecting a safe groundwater profile relative to other sites. Possible sources of these heavy metals include geogenic processes, agricultural inputs (fertilizers, pesticides), and anthropogenic activities. The results suggest minimal industrial contamination, which shows the low-risk concerns in the area. This pattern shows the strong influence of industrial activities such as mining, smelting, and waste discharge in shaping groundwater quality, and it emphasizes the urgent need for targeted remediation and monitoring in high-risk regions to protect public health.

Distribution of Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr) concentrations in groundwater across the countries

Each figure represents the relative contribution of each country to the total concentration of a specific heavy metal, expressed as a percentage. This approach enables a direct comparison of contamination patterns across metals and countries, highlighting the dominant sources, whether geogenic or anthropogenic, that drive groundwater pollution in each region.

IJETRM
International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

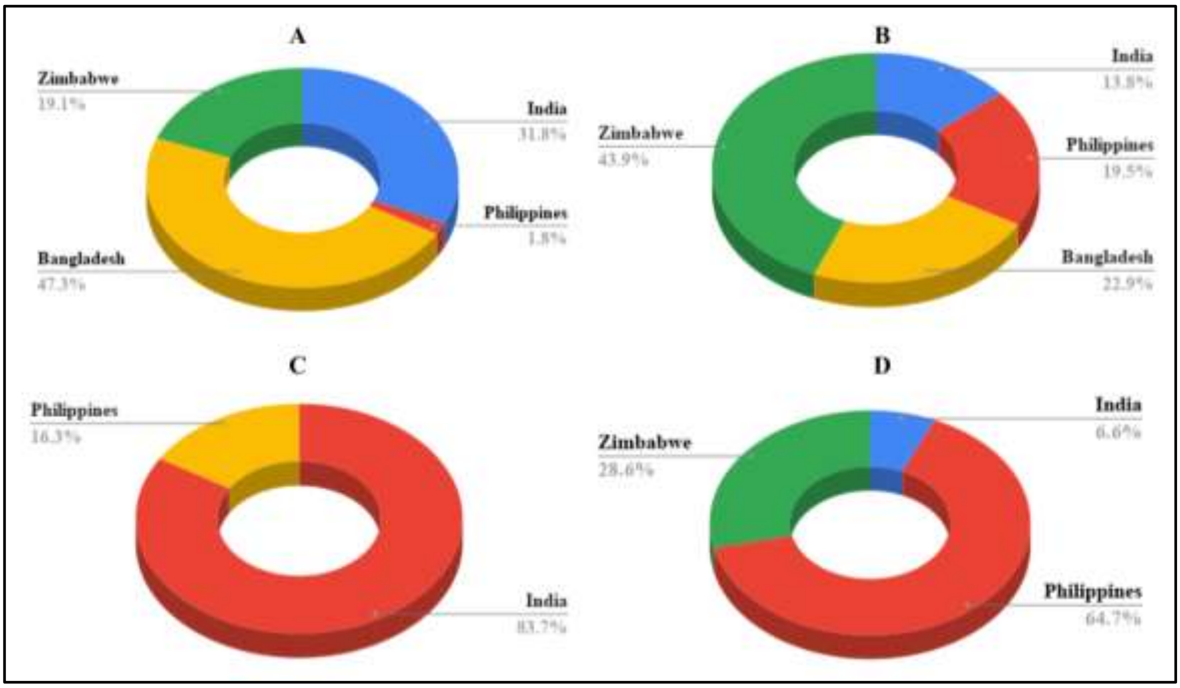

Figure 3. Heavy Metal Concentration in Ground Water across different countries (a) Lead; (b) Cadmium; (c) Arsenic; (d) Chromium.

Figure 3 provides a comprehensive picture of how heavy metal contamination in groundwater varies across countries and metals, revealing both anthropogenic and geogenic drivers. Lead contamination is dominated by Bangladesh (47.3%), India (31.8%), and Zimbabwe (19.1%), with the Philippines contributing only 1.8%. The primary sources are shipbreaking yards in Bangladesh, industrial effluents and poorly managed landfills in India, and the unlined Richmond landfill in Bulawayo, Zimbabwe. In contrast, Cadmium contamination shows Zimbabwe as the largest contributor (43.9%), followed by Bangladesh (22.9%), the Philippines (19.5%), and India (13.8%). Cadmium rich wastes such as batteries and electronics in Zimbabwe, shipbreaking and industrial activities in Bangladesh, mining disasters in Marinduque, Philippines, and localized hotspots in India are the main causes of the Cadmium contamination in Groundwater within these countries. Arsenic contamination presents a different pattern, with India overwhelmingly dominant at 83.7% due to both geogenic sources in the Gangetic Plain and anthropogenic inputs in Maharashtra, while the Philippines contributes 16.3% from ultramafic geology and historical mining. Bangladesh and Zimbabwe are absent in this dataset, reflecting site specific sampling rather than a lack of Arsenic problems globally. Chromium contamination is led by the Philippines (64.7%), followed by Zimbabwe (28.6%) and India (6.6%), with Bangladesh absent. The Philippines' share is explained by ultramafic geology and mining tailings, Zimbabwe's by landfill leachate, and India's by localized industrial activities such as textile dyeing and leather tanning.

Taken together, these figures highlight that contamination is highly metal specific and shaped by distinct sources. Lead and cadmium are primarily anthropogenic, linked to shipbreaking, industrial effluents, and waste mismanagement. Arsenic is largely geogenic in India's alluvial aquifers, though industrial discharges also contribute. Chromium reflects both natural geology (Philippines) and anthropogenic waste disposal (Zimbabwe, India). The heterogeneity across countries underscores that no single narrative explains heavy metal contamination globally; instead, each metal and each location demand tailored monitoring, remediation, and regulatory strategies. Addressing shipbreaking in Bangladesh, improving landfill engineering in Zimbabwe, strengthening industrial effluent controls in India, and mitigating mining legacies in the Philippines would collectively reduce the majority of contamination burdens identified in this comparative analysis.

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

ACKNOWLEDGEMENT

The researchers wish to convey sincere appreciation to the faculty of the Civil and Allied Department, as well as the Environmental Science and Chemical Technology Department, for continuous academic support and valuable guidance throughout the conduct of this systematic review. The authors also express the deepest gratitude to the adviser, Ms. Gecelene Estorico, whose professional insight, constructive feedback, and dedicated mentorship significantly contributed to the quality and completion of this work. Lastly, the researchers acknowledge the collective effort of the entire research team, whose cooperation, commitment, and sense of shared responsibility were integral to the successful completion of this study.

CONCLUSION

This systematic review highlights that groundwater contamination by heavy metals—specifically Lead (Pb), Cadmium (Cd), Arsenic (As), and Chromium (Cr)—remains a significant environmental and public health concern across different regions. The findings consistently show that both geogenic processes and anthropogenic activities contribute to the presence of these metals in groundwater, with higher concentrations commonly associated with industrial areas, mining sites, agricultural activities, and improper waste disposal practices.

Comparative analysis with World Health Organization (WHO) drinking water standards reveals that many reported concentrations exceed permissible limits, particularly in heavily industrialized and mining-affected regions. These exceedances correspond to elevated risk levels, including both non-carcinogenic and carcinogenic health risks, as indicated by hazard quotient (HQ) values greater than 1 and increased incremental lifetime cancer risk (ILCR). Among the metals studied, Arsenic and Chromium frequently present critical risks due to the carcinogenic properties, while Lead and Cadmium contribute significantly to neurological and renal health effects.

The results also demonstrate clear spatial variability in contamination levels, emphasizing that groundwater quality is strongly influenced by local environmental conditions, geological characteristics, and the intensity of human activities. Regions with limited industrial influence generally show lower or acceptable risk levels, whereas areas with intensive anthropogenic inputs consistently exhibit high to very high contamination levels.

Overall, the study underscores the need for continuous monitoring, stricter regulation of pollution sources, and the implementation of effective groundwater management and remediation strategies. Addressing heavy metal contamination is essential to protect public health, maintain environmental sustainability, and ensure the long-term safety of groundwater as a vital freshwater resource.

REFERENCES

[1] Al-Jumaily, E. F., Al-Samarraie, M. F. S., & Al-Mallah, N. M. (2024). Assessment of heavy metals concentration and health risk assessment in groundwater sources of Babylon Governorate, Iraq. *Journal of Cardiovascular Disease Research, 15*(3), 1–12. https://www.jchr.org/index.php/JCHR/article/view/9835

[2] Ali, H., Khan, E., & Ilahi, I. (2024). Heavy metal (Pb, Cd and Cr) contamination and human health risk assessment in groundwater of District Swabi, Khyber Pakhtunkhwa, Pakistan. *Cogent Engineering, 11*(1), Article 2391654. https://doi.org/10.1080/23311916.2024.2391654

[3] Alshehri, M. A., & Abdel-Salam, E. M. (2025). Assessment of heavy metal contamination in groundwater and associated health risks in arid regions. *Toxics, 13*(5), Article 333. https://doi.org/10.3390/toxics13050333

[4] Baculi, R., Ramos, H., & Baculi, R. (2020). Mercury and other heavy metals in groundwater in the abandoned mercury mine in Puerto Princesa City, Philippines. *ResearchGate*. https://www.researchgate.net/publication/343904718

[5] Balali-Mood, M., Afshari, R., & Zojaji, R. (2019). Toxic mechanisms of five heavy metals: Mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology, 7*, Article 18. https://pmc.ncbi.nlm.nih.gov/articles/PMC6236535/

[6] Briffa, J., Sinagra, E., & Blundell, R. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon, 6*(9), Article e04691. https://doi.org/10.1016/j.heliyon.2020.e04691

[7] Cleveland Clinic. (2023). *Heavy metal poisoning (heavy metal toxicity)*. In StatPearls. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK560920/

[8] Gupta, V., Lal, K., & Uttreja, M. (2019). *Contamination of heavy metals in India: Health effects and remediation measures*. The Energy and Resources Institute.

International Journal of Engineering Technology Research & Management (IJETRM)
Journal Article
https://ijetrm.com/issue/

[9] Hoang, T. C., & Dinh, N. T. (2025). Assessment of heavy metal contamination in groundwater and health risk assessment in Hanoi, Vietnam. *Scientific Reports, 15*, Article 88783. https://doi.org/10.1038/s41598-025-88783-x
[10] Islam, M. S., Ahmed, M. K., & Habibullah-Al-Mamun, M. (2016). Spatial variation of heavy metals and ecological risk assessment around ship-breaking yards in Bangladesh. *Cogent Engineering, 3*(1), Article 1140001. https://doi.org/10.1080/23311843.2016.1140001
[11] Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009
[12] Nwankpa, C. C., Obiagwu, C. C., & Edeogu, C. E. (2025). Heavy metal pollution index and ecological risk assessment of groundwater resources in Nsukka, Enugu State, Nigeria. *HydroResearch, 25*, Article 23. https://doi.org/10.1016/j.hydres.2025.10023
[13] Patel, M., Patel, S., & Dave, R. (2023). Water quality degradation due to heavy metal contamination: Health impacts and eco-friendly approaches for heavy metal remediation. *Toxics, 11*(10), Article 853. https://doi.org/10.3390/toxics11100853
[14] Rahman, M. M., & Siddiqua, M. (2025). Analysis of heavy metal contamination in groundwater and its health risk assessment in industrial areas of Bangladesh. *Journal of Water and Health, 23*(5), 630–642. https://doi.org/10.2166/wh.2025.123
[15] Rahman, M. M., Bodrud-Doza, M., & Islam, A. R. M. T. (2025). Heavy metal contamination and associated health risk assessment in groundwater resources of Noakhali District, Bangladesh. *Frontiers in Water, 7*, Article 1694963. https://doi.org/10.3389/frwa.2025.1694963
[16] Rani, A., Kumar, R., & Yadav, A. (2022). Human health risk assessment of heavy metals in groundwater used for drinking and irrigation purpose in Mathura city, Uttar Pradesh, India. *Environmental Science and Pollution Research, 29*(54), 81578–81593. https://pmc.ncbi.nlm.nih.gov/articles/PMC9793032/
[17] RSC Publishing. (2014). *Heavy metals in water: Presence, removal and safety*. Royal Society of Chemistry.
[18] Shakoor, A., Arif, M. S., Yasmin, F., Shehzad, A., & Farooq, M. A. (2024). Health risk assessment of heavy metals in groundwater used for drinking purposes in District Charsadda, Pakistan. *Journal of Water and Health, 22*(10), 1972–1987. https://doi.org/10.2166/wh.2024.058
[19] Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Experientia Supplementum, 101*, 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6
[20] World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed.). WHO.
[21] World Health Organization. (2022). *Chromium in drinking-water: Background document for development of WHO Guidelines for drinking-water quality*. https://iris.who.int/server/api/core/bitstreams/1b7a285e-3635-45dd-a1a9-6068c8fbe173/content
[22] Zulkifli, N. A., Abdullah, M. H., & Nan, W. C. (2021). Assessment of heavy metals contamination in groundwater at Langkawi Island. *Journal of Mechanical Engineering, SI 10*, 157–168. https://jmeche.uitm.edu.my/wp-content/uploads/2021/11/9_SI_10_1570634912.pdf