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HEAVY METAL CONTAMINATION IN GROUND WATER: SOURCES, HEALTH RISKS AND REMEDIATION TECHNOLOGIES

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Abstract

Groundwater is one of the most vital sources of freshwater for drinking purposes, agricultural activities, and industrial use all over the world. Unfortunately, groundwater water quality is facing severe threats of contamination with heavy metals like arsenic, lead, cadmium, chromium, and nickel. These metals are stable in nature and cannot be degraded by biological means; in addition, they have the potential to bio accumulate in living organisms. Therefore, heavy metals pose severe threats to the environment and human health. Heavy metals can enter groundwater systems through geological and anthropogenic activities. Geological activities include natural weathering of rocks and dissolution of minerals in groundwater. Anthropogenic activities include mining activities, industrial effluent discharge into water bodies, agricultural activities, and poor waste management practices. Prolonged exposure to groundwater containing heavy metals may cause various diseases in humans, including neurological disorders, kidney damage, developmental abnormalities, and cancer. Due to low velocities and low self-purification capacity of groundwater systems, it is difficult to remove heavy metals once they have entered groundwater systems. In recent years, various technologies like adsorption, membrane filtration, ion exchange, chemical precipitation, and bioremediation have been developed to remove heavy metals from groundwater systems. This review aims to highlight major sources of heavy metal contamination in groundwater, risks to human health, and available remediation strategies, with emphasis on sustainable management practices and monitoring techniques to maintain groundwater quality.

INTRODUCTION

Being important freshwater resource, groundwater is reliable for drinking. It is used for crop irrigation and in industries in regions where surface water is scarcely available (Sharafi & Salehi, 2025). The infiltration of heavy metals, for example arsenic (As), lead (Pb), nickel (Ni), chromium (Cr), and cadmium (Cd), in aquifers is a serious environmental and human health concern because of their bio-accumulative, persistent and toxic nature (Al-Tamimi et al., 2025). Heavy metal pollution basically means addition of heavy metals in groundwater in concentration above permitted levels in drinking water which cause health impacts including neurological problems, organ damage, and cancer in the long run (Kumar & Maurya, 2025). Natural (geogenic) processes such as rock weathering and soil mineral dissolution, and human activities such as mining, agricultural run-off and inappropriate industrial waste disposal increase the addition of these metals in aquifers that result in groundwater pollution (Hossain et al., 2025; Sharafi & Salehi, 2025). Due to slow recharge rates, limited natural dilution, difficulty in detection and removal heavy metals, groundwater is at more risk of being polluted (Crini et al., 2019). Heavy metal occurrence in groundwater is increased world-wide because of unsustainable industrial practices, rapid urbanization, and population increase and it is a serious public health and water security problem (Zakir-Hassan et al., 2025).

1. Major Heavy Metals Found in Groundwater

Polluted groundwater contains unique geochemical properties bearing heavy metals that cause adverse health effects. Even at low concentration, inorganic arsenic is highly toxic and causes cancer. Especially in South and Southeast Asia, it is the most common groundwater contaminant (Sadee et al., 2025). Lead levels often exceed drinking water standards due to industrial discharge and plumbing system corrosion, and long-term exposure is connected to neurological, renal, and cardiovascular conditions (Sharafi & Salehi, 2025). Cadmium is significant for its persistence and kidney toxicity and is commonly found with other heavy metals in industrial areas and is a major contributor to health risk indices (Sharafi & Salehi, 2025). Mercury remains a concern due to its neurotoxic effects and potential to bio-accumulate within food webs, despite being present in lower concentrations. Particularly hexavalent forms of chromium is commonly found above permissible limits in industrially impacted aquifers which pose carcinogenic risks, as illustrated in Fig.01 (Zakir-Hassan et al., 2025). Near mining and industrial sites, nickel is found in groundwater which is known for non-carcinogenic but chronic health effects (Zakir-Hassan et al., 2025). Apart from these heavy metals copper (Cu), manganese (Mn) and zinc (Zn) are also being closely watched for the possible harm they could cause at high concentrations to environment and human health (Islam et al., 2025). In order to prevent damage to public health, the presence of heavy metals in groundwater requires careful monitoring and focused remediation activities.

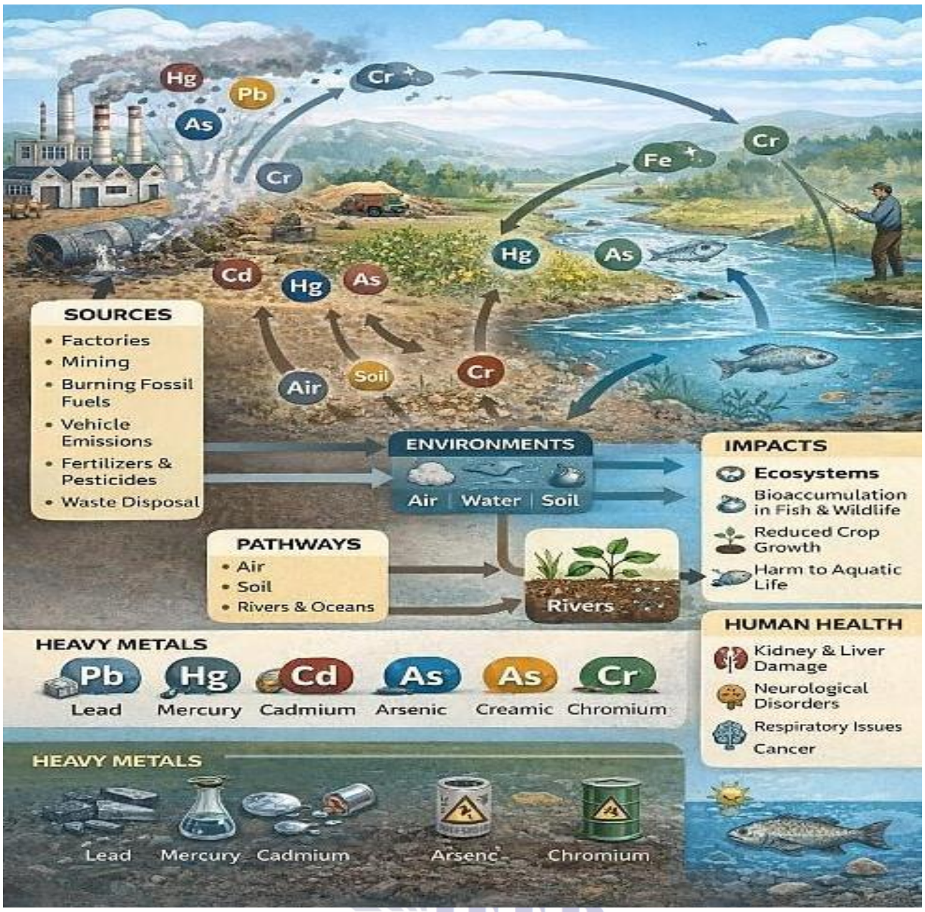

Fig.01: Major heavy metals in groundwater

2. Sources of Heavy Metal Contamination

Anthropogenic (human) and geogenic (natural) sources of heavy metal contamination in groundwater together affect the degree and severity of pollution in aquifers around the world. As a result of natural geological processes and water-rock interactions, metals including arsenic, chromium, nickel, and manganese are released into groundwater systems through volcanic activity, mineral dissolution, and rock weathering (Rashid, Ayub, et al., 2023). Hydro geochemical activity is influenced by basin geology and redox conditions.(Aullón Alcaine et al., 2020). On the other hand, since cities and industries have grown rapidly, man-made sources have increased dramatically and now frequently account for the majority of heavy metal inputs into groundwater. Mining operations release metals during ore extraction and tailings disposal, which contributes to acid mine drainage and increased metal mobility (Rashid, Ayub, et al., 2023). Hazardous metals are directly injected by discharges from manufacturing industries, metal processing and chemical facilities into aquifers through effluents and leakage (Afzal et al., 2024). Agricultural products such as fertilizers and pesticides along with urban runoff from roads, construction and atmospheric deposition causes the leaking of cadmium and lead into soil and groundwater (Akhtar et al., 2021). Furthermore, waste disposal, landfills, sewage and wastewater leakage further contaminate ground water with a group of heavy metals through filtration and subsurface transport, as shown in the Table 01 (Ravindiran et al., 2023).

Table 01: Sources of Heavy Metal Contamination in Groundwater

Source Category	Specific Source	Mechanism of Contamination	Metals	Reference
Geogenic (Natural)	Rock weathering	Dissolution of minerals during water–rock interaction	As, Cr, Ni, Mn	(Rashid, Ayub, et al., 2023)
	Volcanic activity	Release of metal-rich materials into soil and aquifers	As, Cr	(Rashid, Ayub, et al., 2023)
	Mineral dissolution	Hydro-geochemical reactions influenced by basin geology and redox conditions	As, Mn, Ni	(Aullón Alcaine et al., 2020)
Anthropogenic (Human)	Mining activities	Ore extraction, tailings disposal, acid mine drainage increasing metal mobility	As, Cd, Pb, Cr	(Rashid, Ayub, et al., 2023)
	Industrial discharge	Effluents and leakage from manufacturing and chemical plants into aquifers	Pb, Cr, Cd, Hg	(Aullón Alcaine et al., 2020)
	Agriculture	Fertilizers and pesticides leaching into soil and groundwater	Cd, Pb	(Akhtar et al., 2021)
	Urban runoff	Road dust, construction debris, atmospheric deposition	Pb, Zn, Cd	(Akhtar et al., 2021)
	Waste disposal & landfill	Filtration and subsurface transport of leachates	Mixed heavy metals	(Ravindiran et al., 2023)
	Sewage & wastewater leakage	Infiltration into groundwater systems	Cd, Pb, Cr, Ni	(Ravindiran et al., 2023)

4. Transport and Hydro-geochemical Behavior

There are different species of heavy metals in the form of ions, organic complexes, and inorganic complexes and adsorbed species, all of which are of importance with regard to their transportability and reactivity in the environment in terms of solubility and absorption capacity of free and complex species. In contrast, the oxidation-reduction conditions are of importance with regard to metals such as As and Fe valences and complex manor in aquifers (Muhammad et al., 2025).). PH and redox potential, two physicochemical properties, have a major impact on the dynamics of metal specification. Metal hydroxides are soluble in lower pH levels, which increase their mobility (Qiu et al., 2026). Adsorption and desorption processes on the surface of minerals and organic matter regulate the speciation of metals in the solid and liquid phases. However, the alteration in pH, ionic strength, and the concentration of competitive ions may cause instability in the adsorbed metals and transport them from the groundwater (Miranda et al., 2022). The complexation and cation exchange processes, which are mediated by organic and geological phases such as clay and oxides, determine the bioavailability of the fraction of the available heavy metals to the ecosystem as well as the human population (Fig.02). However, the effectiveness of this process can be limiting or enhancing depending on the conditions of the environment (Ramos-Romero et al., 2026).

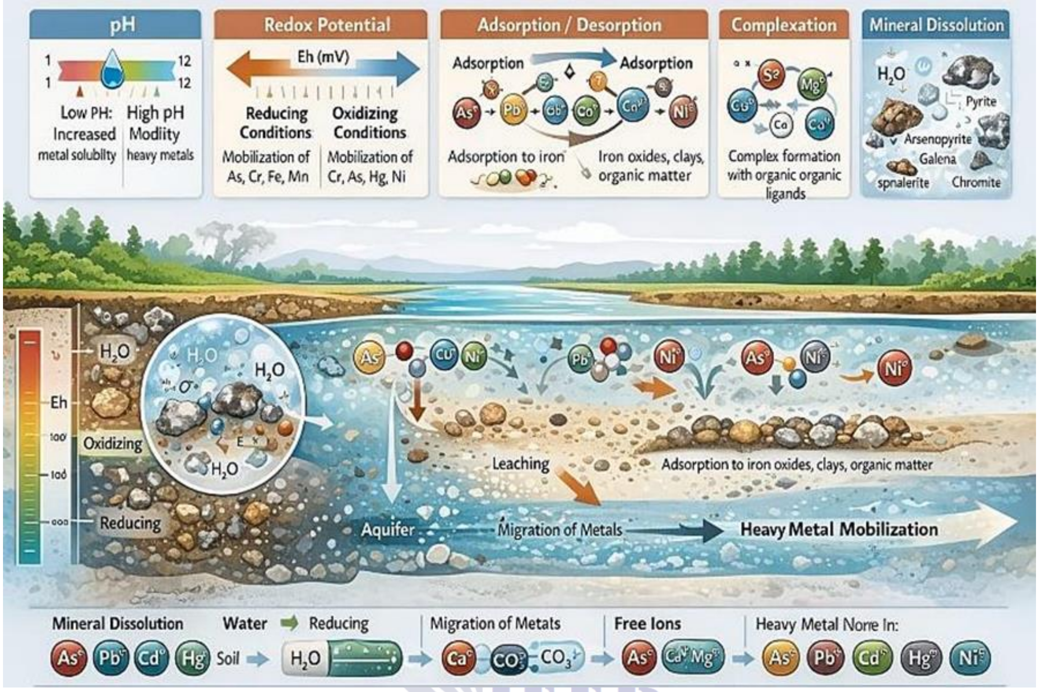

Fig.02: Transport and hydro-geochemical behavior of heavy metals in groundwater

5. Identifying and Tracking Methods

Pollutants and spatial progressive variations in groundwater can be precisely identified by special sampling methods in different evaluating periods. Grab sampling method is used in order to reserve the metal toxins by using acidified bottles to avoid precipitation. This is done to ensure that unadulterated groundwater samples are sent to laboratories for examination (Narayanan et al., 2025). Similarly, the application of time-integrated passive sampling techniques such as Diffusive Gradients in Thin Films (DGT) can provide averaged concentrations of labile metal species in addition to discrete samples. However, standardization and calibration are difficult in heterogeneous aquifers (Mukherjee et al., 2021). Trace metal quantification techniques, however, still mainly employ traditional analytical techniques in the laboratory setting. High sensitivity and precision are achieved by the traditional spectroscopic techniques of Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), and ICP Mass Spectrometry (ICP-MS). Although AAS has remained a widely used technique for single-element analysis in spite of its limitations, ICP-MS and ICP-OES offer the ability to perform multi-element analysis in a single run (Sati et al., 2026). Additional avenues for identifying particular metal species or complicated matrices are offered by other spectroscopic techniques such ion chromatography in conjunction with optical detectors and laser-induced breakdown spectroscopy (LIBS) (Amdeha, 2024). The goal of new sensor-based detection systems and field testing is to close the accuracy gap between in-situ monitoring and laboratory testing. Near real-time field assessments with improved selectivity and smaller equipment footprints are made possible by portable electrochemical sensors that use nanomaterial (graphene, carbon nanotubes, MOFs) in conjunction with methods like differential pulse voltammetry (DPV) or square-wave voltammetry (SWV) to achieve low detection limits and quick response (Mukatayeva et al., 2025). Remote monitoring, automatic data transmission, and predictive modeling of heavy metal trends are made possible by the integration of chemical sensors with IoT and machine learning frameworks as shown in the Table 02, however, issues with sensor stability, calibration drift, and interference from intricate groundwater matrices still exist (Anchidin-Norocel et al., 2025).

Table 02: Detection and Monitoring Techniques for Heavy Metals in Groundwater

Category	Technique/ Method	Principle/ Purpose	Advantages	Limitations	Reference
Sampling Methods	Grab Sampling (pre-cleaned bottles + acidification)	Collection of discrete groundwater samples; acidification prevents precipitation and preserves metal species	Simple, widely used, standardized protocols	Snapshot data only; may miss temporal variations	(Narayanan et al., 2025)
	Quality Control (blanks, duplicates, certified standards)	Ensures data reliability and avoids contamination	Improves accuracy and reproducibility	Increases cost and processing time	(Narayanan et al., 2025)
	Diffusive Gradients in Thin Films (DGT)	Passive, time-integrated measurement of labile/bioavailable metal fractions	Reduces transient fluctuation effects; measures bioavailable forms	Calibration challenges in heterogeneous aquifers	(Mukherjee et al., 2021)
Laboratory Analytical Techniques	Atomic Absorption Spectroscopy (AAS)	Measures absorption of light by free metal ions	Reliable, cost-effective for single elements	Low throughput; matrix interference	(Sati et al., 2026)
	ICP-OES	Optical emission from plasma-excited atoms	Multi-element analysis; good sensitivity	Expensive instrumentation	(Sati et al., 2026)
	ICP-MS	Mass-based detection of ions	Very high sensitivity; trace-level detection; multi-element capability	High cost; skilled operators required	(Sati et al., 2026)
	Laser-Induced Breakdown Spectroscopy (LIBS)	Plasma emission from laser-ablated sample	Rapid analysis; minimal preparation	Matrix effects; lower precision than ICP-MS	(Amdeha, 2024)
	Ion Chromatography (with optical detectors)	Separation and detection of metal species	Good for speciation studies	Requires complex calibration	(Amdeha, 2024)
Field Testing &	Portable Electrochemical	Electrochemical detection using	Low detection limits; rapid	Fouling; calibration drift	(Mukatayeva et al., 2025)

Sensor-Based Detection	Sensors (DPV, SWV)	nanomaterial (graphene, CNTs, MOFs)	response; portable		
	IoT + Machine Learning Integrated Sensors	Real-time monitoring and predictive modeling	Remote monitoring; automated data transmission	Stability issues; matrix interference	(Anchidin-Norocel et al., 2025)

6. Hazards to Health from Heavy Metals

Because of their persistence, bio accumulative nature, and capacity to have both short-term and long-term negative impacts, heavy metals in ground water provide serious health hazards to humans. Assessing the public health implications of contaminated water requires an understanding of exposure routes, toxicity mechanisms, organ-specific affects, carcinogenic potential, and susceptible potentials.

6.1 Routes of Exposure

Ingestion, skin contact, and, to a lesser extent, inhalation of aerosolized dust or droplets are the main ways that people are exposed to heavy metals in contaminated groundwater. Internal accumulation and associated health problems can result from consuming groundwater containing high levels of arsenic , lead, cadmium, chromium, and mercury, as shown in the Fig.03 (Nusrat Ehsan et al., 2025).

6.2 Chronic and Acute Toxicology

Acute toxicity may lead to organ damage, neurological disorders, or gastrointestinal upsets and may be immediate or follow shortly after the administration of large doses of the drug (Latif et al., 2024). On the other hand, toxicological studies have pointed to the fact that long-term exposure to low to moderate doses of the drug is more detrimental to health. For instance, long-term exposure to metals like arsenic and cadmium, often at doses lower than the permissible limits, may lead to systemic toxicity, endocrine disruption, and cumulative organ damage, as displayed in the Fig.03 (Babuji et al., 2023). Drinking water containing arsenic and lead, when consumed chronically, may be associated with cumulative risk indices that exceed the safe limits of health consequences, both carcinogenic and non-carcinogenic, following lifetime exposure (Sharafi & Salehi, 2025).

6.3 Effects Particular to Organs

Strong neurotoxins include lead and mercury. Lead interferes with neurotransmission and neurodevelopment, especially in children, which leads to behavior and cognitive impairments. In a similar vein, mercury, especially its organic form known as methyl mercury, interferes with myelination, which leads to neurodegenerative changes, thereby impairing cognitive and motor functions (Jomova et al., 2025). Lead and cadmium disrupt the processes of kidney filtration, leading to kidney damage, which predisposes an individual to kidney diseases. The kidney tissues are highly susceptible to the adverse effects of heavy metals (Babuji et al., 2023). Due to its detoxifying capacity, the liver is highly susceptible to the adverse health effects of prolonged exposure to heavy metals, such as arsenic and cadmium, which disrupt liver cell functions (Fig.03), leading to instability in the liver's metabolism (Latif et al., 2024).

6.4 Carcinogenic Risks

There are many heavy metals that are either carcinogenic or possess the potential to become so. Because of the oxidative effects as well as DNA, bladder, lung, skin, and gastrointestinal cancers are closely related with long-term exposure to drinking water that contains arsenic, as mentioned in the Fig.03 (Ansari et al., 2024). Similarly, long-term exposure to chromium as well as cadmium has been found to be closely related with increased cancer risk indices, usually above the maximum limits, as part of health risk analysis for contaminated groundwater, especially for communities that are already at risk (Sharafi & Salehi, 2025).

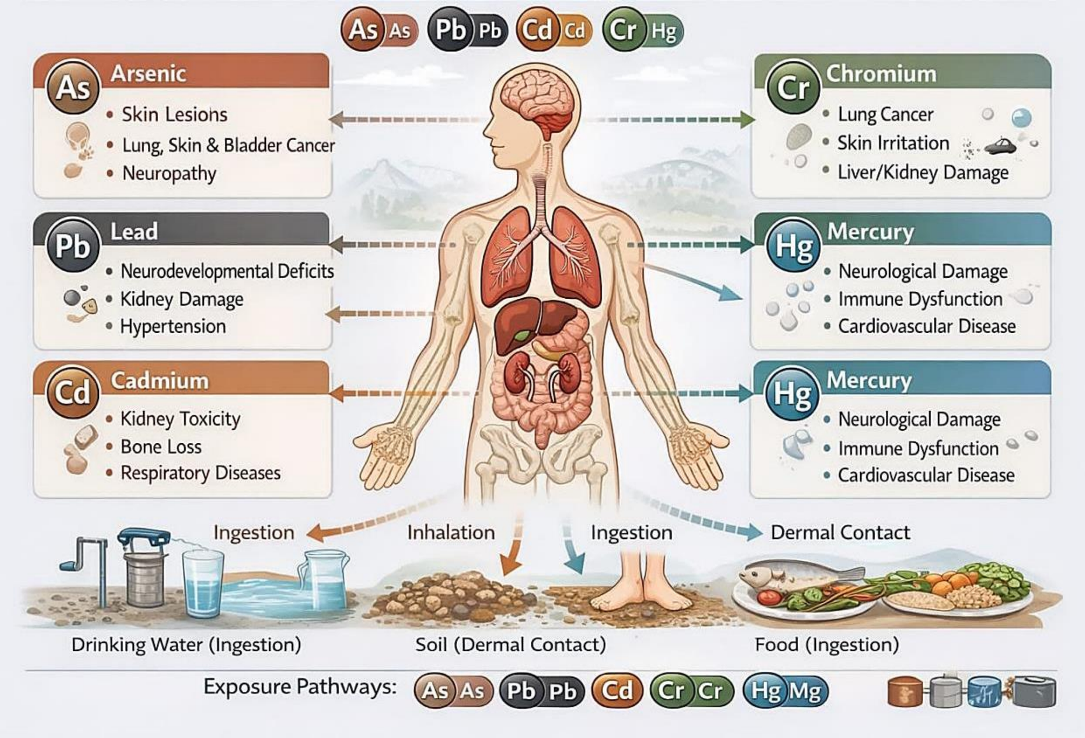

Fig.03: Health effects of heavy metals exposure

7. Environmental and Ecological Impacts

When heavy metals contaminate the groundwater the toxins soak into the soil and absorbed by the crops, making our food supply unsecure and damaging plant growth. These poisons then move up the food chain, becoming concentrated and dangerous as they pass from plants to animals and eventually to humans. So, finally polluted water flows into the riverine lakes, killing fishes and destroying the natural balance of aquatic system. When metals pass in the soil through polluted irrigation water or leachate then the physicochemical features of soil such as water retention, hydraulic conductivity, and microbial function are changed. This leads to a worsening in soil quality and raises the metal release into groundwater and plant roots (Yadav et al., 2025). In agricultural areas, high level of heavy metal in soil cause physiological disruption in plants and decreased crop yield by interfering with photosynthesis, nutrient uptake, and metabolic processes. Crops such as rice and vegetables also stores toxic metals in edible their edible parts, which creates food safety risks (Rashid, Schutte, et al., 2023). Particularly in such cases when irrigation with contaminated water is continuous, these soil and crop connections increase the risk of metal exposure through food consumption and promoting the entry of metals into the human food chain (Mustapha et al., 2025). Moreover, the harmful effects of heavy metal toxins are seen at all trophic levels and these metals reach aquatic ecosystems, where they accumulate in fish and other organisms, alter species composition, and disrupt ecosystem function and biodiversity (Nusrat Ehsan et al., 2025; El-Sharkawy et al., 2025).

8. Regulatory Frameworks, Risk Assessment and Management Strategies

World Health Organization (WHO) and national standards are used to set safe standard for drinking water while tools like Human Health Risk Assessment (HHRA) and the Heavy Metal Pollution Index are used to identify highly effected areas and calculate exposure, respectively (Latif et al., 2024; Zakir-Hassan et al., 2025). The assessment methods highlight the need for cleanup measures and government actions in the areas where heavy metal levels exceed safe limits (N. Ehsan et al., 2025). Source-based health risk models help authorities focus on major pollution sources like industrial waste, mining activities and agricultural run-off (Han et al., 2023). Governments use better monitoring and strict rules to stop factories from discarding waste to manage groundwater pollution. It is made sure that farmers use safer methods to reduce chemical runoff into the earth. Experts use Managed Aquifer Recharge (MAR) strategy to replenish groundwater and help maintain safe and clean groundwater (Rashid, Ayub, et al., 2023).

9. Remediation Technologies for Heavy Metal Removal

Traditional methods of cleaning groundwater contaminated with heavy metal are replaced by the environmentally friendly technologies that treat dissolved metals both in-situ and ex-situ. Reactive media such as zero-valent iron, zeolites, bio-char, and composite materials capture contaminated groundwater and remove heavy metals through the process of adsorption, ion exchange, surface complexation, and precipitation methods. . These materials are often used in **permeable reactive barriers (PRBs)** that is a passive in-situ method that has been broadly studied and offers long term remediation with little energy requirements (Budania & Dangayach, 2023; Song et al., 2021). In order to overcome the difficulties associated with complex contaminant combinations, recent developments also include bio-augmented PRBs (Bio-PRBs), in which microbial activity improves heavy metal transformation and immobilization (Lin et al., 2025). Because of their large surface area and adjustable surface chemistry, nanomaterial have become very successful adsorbents and reactive agents for the removal of metals, allowing for the effective uptake of Pb, Cd, As, and other metals in groundwater matrices (De Silva et al., 2025). High removal efficiencies are being achieved by optimizing membrane technologies, such as reverse osmosis and advanced polymeric membranes, for the removal of heavy metals from contaminated source waters; nevertheless, fouling and energy consumption continue to be problems (Dawam et al., 2025). Complementary techniques like microbial mineralization, which uses metal-transforming microorganisms to precipitate or sequester metals, have the potential to treat complex groundwater plumes in an economical and sustainable manner (D. Liu et al., 2025).

10. Evaluating and Comparative Analysis of Remediation Techniques

A number of significant criteria are used to evaluate remediation strategies for the groundwater that is contaminated by heavy metals which include the cost, environmental impact, site suitability, and the efficiency with which they remove heavy metals (Zhang et al., 2023). Effective remediation methods remove the contaminant and also reduces the health risks without causing the new pollution (Ghafoor et al., 2023). Traditional techniques such as chemical treatment and excavation, work well but are frequently costly because of their high energy consumption and infrastructural needs (Khalifa et al., 2025). On the other hand green and biological technologies are typically less expensive and they could take longer to produce results (A. Sarker et al., 2023).

Eco-friendly techniques like microbial treatment and phytoremediation are favored since they prevent hazardous byproducts and lessen environmental harm (A. Sarker et al., 2023). Modern techniques such metal-organic frameworks, microbial remediation, an d nanomaterial are better at safely and permanently removing toxins without producing pollution (De Silva et al., 2025). In-situ remediation removes contaminants on the spot, without removing soil or water causing fewer disturbances and also saving money (Akhtar, 2023; Xu et al., 2022). Microbial stimulation and permeable reactive barriers are two examples. The removal of contaminated material for treatment elsewhere is known as ex-situ remediation, which improves control but uses more money and energy (Ghafoor et al., 2023). Conventional methods are frequently employed because they are simple to use however they may not entirely remove all metals and may produce secondary waste (Khalifa et al., 2025; Zhang et al., 2023). New technologies that includes hybrid treatment systems and nanotechnology can improve the selective removal of contaminants and increase treatment efficiency under controlled conditions (Khalifa et al., 2025). Many remediation methods perform well in the laboratories experiments, but they often fail in natural environmental conditions because soil and water systems are highly complex and constantly changing, which affects their overall performance (Sanusi et al., 2025; Xu et al., 2024).

11. Challenges and Limitations in Heavy Metal Groundwater Remediation

Many treatment methods perform well in laboratory studies but they may face difficulties in real groundwater conditions because variations in soil properties, water flow, and types of metals can reduce their effectiveness (Xu et al., 2024; Zhang et al., 2023). Biological and nanomaterial based remediation techniques are very sensitive to the environmental variations, making it difficult to monitor their long term effectiveness or performance under real field condition (De Silva et al., 2025). Many remediation techniques are too much costly. Conventional physical and chemical treatments such as membrane filtration or soil washing requires high initial investments and ongoing expenditures (Aniruddha Sarker et al., 2023a; Xu et al., 2024). Even though they are more expensive, advanced techniques like hybrid systems and nanoparticles perform better (De Silva et al., 2025). Long-term monitoring increases extra expense, making it hard for poorer regions to implement these technologies (Aniruddha Sarker et al., 2023b). Certain remediation systems require continuous care for maintenance to function properly. Microbes and plants are examples of biological methods that depend on variables like pH, temperature, and nutrition (Xu et al., 2024; Zhang et al., 2023). Treatment barriers and other physical systems need regular cleaning and changing of materials and if they are not properly maintained, they stops working properly (Dajin Liu et al., 2025). Certain cleanup techniques may not easily accepted by the local community (Sanusi et al., 2025). For example, techniques involving chemical injection, well construction, or digging land may increase doubt and fear among peoples (Wang et al., 2021). In many locations, there is also a lack of knowledge about the dangers of heavy metals and the advantages of treatment (Ghafoor et al., 2023). Remedial projects may be delayed or abandoned due to a lack of community support (Sanusi et al., 2025).

12. Future Perspective

12.1 Intelligent Monitoring Systems

Future research focus on developing intelligence, real time monitoring systems that can accurately track heavy metal concentration in ground metals (Akhtar, 2023; Xu et al., 2024). Rather than relying on occasional manual sampling, water managers can enhance early warning systems and respond more faster to pollution occurrences by using machine learning, sensor networks, and predictive models (Dajin Liu et al., 2025). GIS and remote sensing are examples of smart monitoring tools that can map contamination patterns and also support better decision making for long term groundwater protection (Dajin Liu et al., 2025).

12.2 Materials for Sustainable Remediation

Current remediation studies highlights the importance of using low-cost and environmentally friendly materials which remove heavy metals without posing damaging effects to the environment (Sanusi et al., 2025). Sustainable groundwater treatment methods such as bio-adsorbents from plant waste and agricultural by-products, biodegradable hybrid membranes and microbe-assisted materials show strong potential (Meftah et al., 2025). Utilizing these resources not only assist to reduce waste but also contributes to international sustainability goals such as the sustainable development goals SDGs (Sanusi et al., 2025).

12.3 Policy improvement and governance

Reducing heavy metal contamination and protecting public health depend strongly on the government regulations and improved groundwater management (Arman et al., 2025). Research indicate that regulations should enforce industrial wastewater standard, increases cooperation between environmental agencies, and align water management with public health and climate resilience goals (Singh et al., 2025).

12.4 Methods of Integrated Management

Combining scientific, social, and policy approaches is essential for managing water resource and reduces heavy metal contamination (Singh et al., 2025). Holistic frameworks improves sustainability and lower future risks, such as combining remediation technology with public health, climate adaption, and land-use planning (Talib et al., 2026). According to research, integrated strategies involving technology, governance, and community involvement can solve several problems at once, such as pollution and climate change (Li et al., 2025).

13. Critical Insight

One of the most critical issues that is not taken into account in studies of groundwater contamination is the long-term presence and transport of heavy metals in aquifers. This is particularly relevant in cases where the main source of contamination is eliminated or removed. Heavy metals can remain bound in aquifer sediments for long periods of time and eventually re-enter the water column by geochemical processes such as changes in pH, redox potential, and solubility of minerals. This is a critical issue that should be taken into account in future studies of groundwater contamination. Most studies are focused on removal processes, but there is less emphasis on preventing re-removal of contaminants after removal processes are initiated. Future studies should be focused not only on efficient removal processes but also on hydro-geochemical processes that affect heavy metals in aquifers. This is a critical issue that could improve the efficiency of groundwater remediation processes.

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