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Arsenic contamination in groundwater sources: Geochemical transformations, health hazards, toxicity and sustainable remediation technologies

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Abstract— *Arsenic contamination of groundwater represents one of the most significant geogenic and anthropogenic environmental health challenges of the modern era. Naturally occurring Arsenic, released through complex geochemical processes involving reductive dissolution of iron oxyhydroxides, oxidative weathering of sulfide minerals, and desorption under alkaline conditions, affects aquifers across Asia, the Americas, and parts of Europe and Africa. Chronic exposure via drinking water leads to Arsenicosis, characterized by skin lesions, cardiovascular disease, neurological impairment, and elevated risks of cancers of the skin, bladder, lung, and other organs. Toxicity is driven primarily by the greater mobility and cellular reactivity of arsenite (As(III)) relative to arsenate (As(V)), involving disruption of enzyme systems, generation of reactive oxygen species, interference with DNA repair, and epigenetic alterations. Regional comparisons reveal extreme contamination in the Bengal Basin (Bangladesh and West Bengal, India), the Red River and Mekong deltas, the Pampa plain of Argentina, and parts of China and the western United States, with concentrations frequently exceeding the World Health Organization guideline of 10 µg/L by one to two orders of magnitude. Sustainable remediation approaches encompass oxidation-coagulation-filtration, adsorption onto iron-based media, ion exchange, membrane processes, and emerging biological and hybrid technologies. This review synthesizes geochemical controls, health and toxicity mechanisms, regional patterns, and technology performance, emphasizing the need for context-specific, low-cost, and environmentally sound solutions that minimize secondary waste and support long-term water security.*

Keywords— ***Arsenic, groundwater, geochemistry, speciation, Arsenicosis, toxicity, remediation, adsorption, oxidation, sustainable technologies***

I. INTRODUCTION

Arsenic (As) is a metalloid that occurs widely in the Earth's crust at average concentrations of about 1.5–2 mg/kg [1]. Although it is found in more than 200 mineral species, its environmental significance is mainly due to its mobilization into groundwater under certain hydrogeochemical conditions. The identification of extensive Arsenic contamination as a public health crisis accelerated in the 1990s following documentation of severe exposure in Bangladesh and West Bengal, India, where tens of millions of people rely on shallow tube wells that inadvertently draw from Arsenic-rich aquifers [2, 3]. Later work revealed similar problems in Vietnam, Cambodia, China, Argentina, Chile, Mexico, the United States, and other parts of the world, including the Argentine Pampa and some parts of the southwestern United States; alkaline pH and high bicarbonate levels favour [4–6].

The World Health Organisation's provisional guideline value for Arsenic in drinking water, set at 10 µg/L in 1993 and confirmed in later updates, is based on epidemiological data linking chronic low-level exposure with skin lesions and internal cancers [7]. Many countries still have older national standards of 50 µg/L, which is why large populations remain exposed. Early 2010s estimates indicated that more than 100–200 million people worldwide were at risk of drinking water containing above 10 µg/L [8, 9].

Arsenic in groundwater is present mainly as inorganic species, arsenate (As(V)) under oxidizing conditions and arsenite (As(III)) under reducing conditions. In natural groundwater, organic methylated forms are generally minor, but they can be formed through microbial activity [10]. Arsenic speciation is critical for determining its mobility, toxicity, and treatability. This review covers geochemical changes that lead to Arsenic release, health risks, and

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molecular mechanisms of toxicity; comparative regional patterns; and the array of sustainable remediation technologies available or under development. The focus is on synthesizing field and laboratory evidence into a coherent framework highlighting both scientific advances and practical constraints.

II. GEOCHEMICAL CHANGES OF ARSENIC

Arsenic enters groundwater through natural weathering and, to a lesser extent, through anthropogenic sources such as mining, smelting, pesticide application, and wood preservatives [1, 6]. The primary natural mechanisms include (i) reductive dissolution of Arsenic-bearing iron oxyhydroxides under anoxic conditions, (ii) oxidative dissolution of sulfide minerals such as arsenopyrite (FeAsS), and (iii) desorption of Arsenic from mineral surfaces at high pH [11–13].

Microbial reduction of Fe(III) oxyhydroxides driven by organic matter decomposition in young alluvial aquifers of the Bengal Basin and Southeast Asian deltas releases co-precipitated or adsorbed Arsenic into solution [2, 14, 15]. Dissolved organic carbon, phosphate and bicarbonate compete for sorption sites and further enhance Arsenic mobility [16, 17]. Redox stratification is typical: shallow aquifers often have higher As(III) proportions, whereas deeper or more oxidizing zones may favour As(V) [18, 19].

In arid and semi-arid environments such as the Argentine Pampa and parts of the southwestern United States, alkaline pH and high bicarbonate levels lead to the desorption of arsenate from iron and aluminium oxides [5, 20]. Arsenic is released from volcanic and geothermal settings by mixing of hydrothermal fluids, as seen in some regions of Chile, Mexico, and the western United States [6, 21].

Table 1. Summary of Arsenic geochemistry and controlling processes: a comparative study.

Region / Setting	Dominant Species	Typical As Range (µg/L)	Primary Mobilization Process	Key References
Bengal Basin (Bangladesh/West Bengal)	As(III) > As(V)	10–1000+	Reductive dissolution of Fe oxyhydroxides	[2, 12, 15]
Red River Delta, Vietnam	Mixed	1–3000	Reductive dissolution + organic matter	[4, 22]
Chaco-Pampean Plain, Argentina	As(V)	10–5000+	High-pH desorption from Fe/Al oxides	[5, 20]
Inner Mongolia, China	Mixed	10–1800	Reducing conditions + high bicarbonate	[23, 24]
Southwestern USA	Variable	<1–>1000	Oxidative sulfide weathering + desorption	[6, 25]

Microbial mediation is essential. Dissimilatory iron-reducing bacteria (e.g., Geobacter and Shewanella) and arsenate-respiring bacteria mediate release and transformation [26, 27]. Sulfate reduction can lead to secondary precipitation of Arsenic sulfides, thereby attenuating dissolved concentrations under strongly reducing, sulphide-rich conditions [28, 29]. Sorption equilibria are further modulated by competitive anions (phosphate, silicate, and bicarbonate) and changes in ionic strength [17, 30].

Anthropogenic inputs are locally important near mining districts or in agricultural regions where Arsenical pesticides are used, but are secondary globally compared to geogenic sources [1]. However, oxidation of sulfide tailings associated with mining activities still produces acid drainage with elevated Arsenic levels in areas such as the western United States, Chile, and parts of Europe [31, 32].

III. ARSENIC IN GROUNDWATER: HEALTH HAZARDS

Arsenicosis is a clinical spectrum caused by chronic ingestion of inorganic Arsenic in drinking water. Early dermatological findings are melanosis (diffuse or spotted hyperpigmentation) and keratosis (hyperkeratotic lesions on palms and soles), which often appear after years of exposure at concentrations above 50–100 µg/L [33, 34]. Progressive exposure increases the risks of skin cancer (Bowen's disease, squamous and basal cell carcinomas) and internal malignancies of the bladder, lung, liver, and kidney [35–37].

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Cardiovascular effects include peripheral vascular disease (historically described as "blackfoot disease" in Taiwan), hypertension and ischemic heart disease [38–40]. Neurological manifestations range from peripheral neuropathy to cognitive deficits, particularly in children exposed in utero or at an early age [41, 42]. Reproductive and developmental outcomes, including increased risk of spontaneous abortion, stillbirth and low birth weight, have been reported in Bangladesh and Chile [43, 44].

At low exposures, dose–response relationships are nonlinear, and individual susceptibility depends on nutritional status, genetic polymorphisms in Arsenic-metabolising enzymes (AS3MT, GSTO), and co-exposure to other contaminants [45, 46]. Populations with low selenium, folate or protein status seem more susceptible [47, 48].

Table 2. Selected epidemiologic findings on health impacts of Arsenic in drinking water.

Region	Exposure Range (µg/L)	Key Health Outcomes Observed	Approximate Population at Risk	References
Bangladesh / West Bengal	10–>1000	Skin lesions, skin/lung/bladder cancer, cardiovascular disease	>50 million	[33, 49, 50]
Taiwan (southwest)	10–>600	Blackfoot disease, skin and internal cancers	Historical cohorts	[38, 36]
Northern Chile	10–>800	Lung and bladder cancer, childhood developmental effects	Hundreds of thousands	[51, 44]
Inner Mongolia / China	10–>1000	Skin lesions, cancer, cardiovascular effects	Tens of millions	[23, 52]
Argentina (Pampa)	10–>1000	Skin lesions, possible cancer elevation	>2 million	[53, 54]

IV. MECHANISMS OF TOXICITY

Inorganic Arsenic toxicity depends on its speciation. As(III) is usually more toxic than As(V) because it has a higher affinity for sulfhydryl groups in proteins and enzymes [55, 56]. After absorption, arsenate can substitute for phosphate in biochemical reactions. Arsenite inhibits pyruvate dehydrogenase, glutathione reductase and other essential enzymes by binding with vicinal thiols [57].

The main mechanism is oxidative stress. Arsenic activates NADPH oxidase and causes mitochondrial dysfunction, generating reactive oxygen species (ROS), which mediate lipid peroxidation, protein oxidation, and DNA damage [58, 59]. Additional enhancement of genotoxicity results from inhibition of DNA repair enzymes (e.g., PARP-1, DNA ligase) and interference with zinc-finger proteins [60, 61]. Epigenetic changes such as DNA methylation and histone modifications have been linked to Arsenic-induced carcinogenesis [62, 63].

Methylation of inorganic Arsenic by the Arsenic (+3 oxidation state) methyltransferase (AS3MT) produces monomethylarsonous acid (MMA(III)) and dimethylarsinous acid (DMA(III)), intermediates that are more toxic than the parent inorganic forms in some experimental systems [64, 65]. Urinary profiles of MMA and DMA are biomarkers of methylation efficiency and susceptibility [45].

Chronic exposure also impairs immune function, disrupts endocrine signalling, and promotes inflammation, contributing to multi-organ pathology [66, 67].

V. COMPARATIVE PERSPECTIVES FROM OTHER REGIONS

The spatial pattern of high groundwater Arsenic is strongly associated with geology and climate. The most severe and extensively studied example is the Bengal Basin, where Holocene sediments derived from the Himalayas host reducing aquifers with median Arsenic concentrations that commonly exceed 50 µg/L and maxima that exceed 1000 µg/L [68, 15]. Similar reductive-release mechanisms have been observed in other deltaic settings in Vietnam and Cambodia [69, 70].

Conversely, the Chaco-Pampean plain of Argentina has oxidizing, high-pH groundwaters where arsenate desorption from iron and aluminium oxides, often associated with

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volcanic ash, leads to widespread contamination [20, 5]. Over large areas, concentrations often exceed 100 µg/L. In China, reducing aquifers in the Datong and Hetao basins and oxidizing systems in other provinces contribute to exposure of tens of millions [71, 9].

North American occurrences are more localized. Elevated Arsenic is documented in the southwestern United States, New England, and parts of the Midwest due to natural mineral dissolution and historical mining [6, 72]. European hotspots are located in Hungary, Romania, and parts of Spain and Italy, and are often associated with geothermal or sedimentary basins [1].

These regional differences show that there is no one geochemical model that applies everywhere, and that successful risk assessment and remediation must take into account local redox conditions, sediment mineralogy and hydrology.

VI. SUSTAINABLE REMEDIATION TECHNOLOGIES

Remediation strategies aim to reduce Arsenic concentrations to below 10 µg/L with minimal cost, energy demand, chemical use, and secondary waste. The conventional methods are oxidation, coagulation-flocculation, adsorption, ion exchange, and membrane filtration [73, 74].

Oxidation of As(III) to As(V) improves subsequent removal, as arsenate is more readily removed by most adsorbents and coagulants. Common oxidants are free chlorine, permanganate, ozone and solid manganese oxides [75, 76]. Coagulation with ferric or aluminium salts, followed by filtration, is still widely used at the community and household scales. Iron-based coagulants are generally more effective than aluminium for Arsenic [77, 78].

Adsorption on iron oxide-coated sand, activated alumina, granular ferric hydroxide, and zero-valent iron have been widely tested [79–81]. Practical success has been seen with household-use filters made from locally available iron materials (e.g. the SONO filter in Bangladesh) [82]. Ion-exchange resins selective for arsenate work well under controlled conditions but are sensitive to competing anions and produce regenerant brine [83].

Membrane processes (nanofiltration, reverse osmosis) achieve high removal efficiencies but are energy-intensive and produce concentrated reject streams [84, 85]. Biological approaches such as microbial oxidation of As(III) and Fe(II) in fixed-bed reactors, and phytoremediation with Arsenic-hyperaccumulating plants (e.g., Pteris vittata), provide potentially less expensive options [86, 87].

Table 3 Comparative effectiveness of Arsenic removal technologies.

Technology	Typical Removal Efficiency (%)	Effective for As(III)/As(V)	Key Advantages	Limitations	References
Fe coagulation-filtration	80–99	Better for As(V)	Low cost, scalable	Sludge disposal, pH sensitivity	[77, 78]
Granular ferric hydroxide	90–>99	Both (after oxidation)	High capacity, simple operation	Media replacement cost	[88, 89]
Activated alumina	70–95	Preferentially As(V)	Regenerable	Competing ions, pH control	[90, 74]
Zero-valent iron filters	80–99	Both	Low-cost materials	Passivation, clogging	[79, 80]
Reverse osmosis / NF	>95	Both	High removal of multiple contaminants	Energy, concentrate disposal	[84, 85]
Biological oxidation + filtration	70–95	As(III) via oxidation	Minimal chemicals	Temperature/microbial sensitivity	[86]

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Hybrid and emerging systems that combine oxidation with adsorption or biological processes show promise for decentralized applications [91, 92]. Sustainability criteria include life-cycle energy use, chemical consumption, residuals management and social acceptability. In resource-limited contexts, technologies that use locally available materials and require minimal maintenance have proven to be more durable [93, 94].

VII. FUTURE DIRECTIONS AND CHALLENGES

Even with substantial scientific advances by 2019, practical barriers still exist. The poor performance and inconsistent performance of many household filters are caused by variable water chemistry, lack of maintenance, and inadequate residual disposal. In rural areas with dispersed populations, centralized treatment is often not feasible. Secondary Arsenic-rich wastes must be safely managed to prevent re-release. The capacity to monitor and enforce regulations varies greatly among the affected countries.

Different literature identified research priorities including: improved understanding of microbial community dynamics driving Arsenic cycling; development of low-cost sensors for speciation; optimization of regenerative adsorbents; and integration of remediation into broader water safety planning [13, 8]. Community engagement and behaviour change interventions are needed to ensure sustained use of safe water sources.

VIII. CONCLUSION

The complex geochemical processes that control redox conditions, mineralogy, organic matter, and competing ions contribute to groundwater Arsenic contamination. These processes have resulted in widespread exposures that continue to pose threats to the health of tens to hundreds of millions of people through dermatological, cardiovascular, neurological, reproductive, and carcinogenic effects. The toxicity results from the biochemical reactivity of arsenite and the oxidative and genotoxic effects of Arsenic metabolism. Regional patterns are indicative of different hydrogeochemical regimes, from reductive alluvial aquifers of South and Southeast Asia to alkaline oxidizing systems of the Americas. A variety of remediation technologies have been developed and tested, including oxidation, coagulation, adsorption, ion exchange, membranes and biological methods. Cost, residual management and local capacity are the main challenges to sustainable, scalable implementation. Long-term solutions need to incorporate geochemical insight, technological innovation adapted to resource constraints, robust monitoring and community participation. It is only coordinated efforts like this that can considerably reduce the global burden of Arsenic exposure and provide safe drinking water to affected populations.

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