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Arsenic geochemistry and human health in South East Asia

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Abstract

Arsenic occurs naturally in many environmental components and enters the human body through several exposure pathways. Natural enrichment of arsenic may result in considerable contamination of soil, water, and air. Arsenic in groundwater can exceed values hundreds of time higher than the concentration recommended for drinking water. Such exposure levels indicate a serious potential health risk to individuals consuming raw groundwater. Human activities that have an impact on the environment may increase the distribution of inorganic arsenic. Abandoned mines are of great concern due to the extremely high arsenic concentrations detected in mine drainage and tailings. Diet, drinking water, air, soil, and occupational exposures are all sources of inorganic arsenic for humans. Interdisciplinary efforts to better characterize the transport of arsenic and reactants that facilitate their release to the environment are important for human health studies. Multi-disciplinary efforts are needed to study diet, infectious disease, genetics, and cultural practices unique to each region to better understand human health risk and to design public health interventions.

Keywords

arsenic; co-factor; exposure; human health; South East Asia

Introduction

Arsenic ranks 52nd in crustal abundance and has an average crustal concentration of 1.8 mg/kg (1). Historically, arsenic was known as a non-essential element that could be used as a poison (2). In 1962, the focus shifted from the effects of arsenic as a poison to the long-term health effects of inorganic arsenic exposure, when Blackfoot disease was discovered by Chen and Wu in Taiwan (3). Tseng et al. (4) found the relationship between long-term exposure to a high-level of arsenic in drinking water and characteristic disease symptoms, including skin lesions, skin cancer, and Blackfoot disease. Ventricular fibrillation caused by arsenic poisoning was also reported by St Petery et al. (5). According to Tseng, many endemic areas of chronic arsenicism had been reported for Poland, Argentina, and Chile (6). Awareness of elevated inorganic arsenic exposure in drinking water increased throughout the world and new instances continue to be reported. Since the early 1990s, numerous

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studies have been conducted to study inorganic arsenic exposure and human health outcomes.

Inorganic arsenic contamination has had a dramatic impact on the contamination of soil and groundwater in many regions of the world. Bangladesh and West Bengal (India) have been identified as the most highly affected by arsenic contamination of groundwater in terms of the magnitude of the population affected by the contamination and the degree of elevated exposure (7–12). Recently, a number of studies in the Mekong River Basin in Cambodia and Vietnam have revealed exposure levels that are comparable to the concentrations observed in Bangladesh (13–29).

Prior health-impact assessments have indicated the strong potential for intersectoral collaboration between several of the South-East Asia (SEAR) countries, but highlighted the need for enhanced collaboration, practice, and policy regarding environmental health issues in the region. The Pacific Basin Consortium recently organized a meeting focused on environment and health at their 13th International Conference in Perth, Australia. A specific session was held therein to address inorganic arsenic geochemistry and human health. The important outcomes of this meeting were to assess the current research on arsenic geochemistry and human health, to bring together scientists for future collaboration, and to identify the key areas of future research in the region. It is vital that researchers develop a better understanding of the interaction between arsenic and other co-exposure factors (heavy metals, nutrition, and infectious agents), the effects of exposure duration, and genetic makeup on arsenic poisoning to clarify the current situation in this region. Furthermore, it is urgent that we understand the unique geochemical features of the region, characterize arsenic exposure pathways, and develop arsenic remediation technology in South East Asia.

Our objectives in this review are (a) to summarize the source and distribution of arsenic in the environment, (b) to describe the exposure levels surrounding of abandoned mining areas with particular reference to case studies from South Korea, (c) to summarize the health effects associated with inorganic arsenic exposure and known modifiers that introduce variability in biological response, and (d) to make recommendations for multi-disciplinary strategies to reduce the global impact of arsenic.

Sources and distribution of arsenic

Environmental source of arsenic

Arsenic is ubiquitous in the environment as a result of geological contribution as well as from anthropogenic sources. Arsenic is widely distributed in the earth's crust and commonly associated with metal sulfide ores, in which isomorphous replacement occurs within the lattice between arsenic and sulfur due to their chemical similarity. Elevated concentrations of arsenic can also be found in many oxide minerals and hydrous metal oxides, either as a component of the mineral structure or as sorbed species. The weathering of rocks and minerals appears to be a major source of arsenic found in soils and groundwater. The nature of arsenic in soil is controlled by the lithology of the parent rock materials, volcanic activity, weathering history, transport, sorption, biological activity, and precipitation. The elevated concentrations of arsenic in groundwater derive directly from reductive dissolution of iron oxyhydroxides which naturally occurred in aquifer.

Human activities considered to be the sources of arsenic contamination include mining activities; metal smelting; fossil fuels combustion; waste incineration; irrigation; the application of pesticides, herbicides, and fungicides; crop desiccants, wood preservatives, and food additives for cattle and poultry.

Arsenic contamination of water, soil, and air

The guideline value for inorganic arsenic in drinking water was reduced from 50 μg/L to 10 μg/L by the World Health Organization (WHO) in 1993 and by the United States Environmental Protection Agency (US EPA) in 2001. Many countries, particularly developing countries, still use the 50 μg/L value as standard for arsenic partially because of lack of adequate analytical instruments for lower arsenic concentrations in water.

Elevated concentrations of arsenic in drinking water (above 50 μg/L) have been reported in several countries, including Argentina, Chile, China, Mongolia, Taiwan, Nepal, Japan, Mexico, Poland, Vietnam, and the USA (30). Local-scale problems of arsenic contamination of groundwater have been reported by some countries, and new cases are continually discovered. Clearly, groundwater contaminated by arsenic can be found all over the world, regardless of the climate condition. However, serious arsenic contamination can usually be observed in shallow alluvial and deltaic aquifers of Holocene age.

Arsenic has been suggested to be introduced into groundwater through the (i) oxidation of aquifer arsenical pyrite and other arsenic-bearing sulfide minerals, (ii) reductive dissolution of arsenic-rich Fe(III) oxyhydroxides and Al-hydroxides present in aquifer, and (iii) exchange of adsorbed arsenic with other competitive anions (phosphate, bicarbonate and silicate). Nevertheless, the reductive dissolutions of arsenic-rich Fe(III) oxyhydroxides and/or Al-hydroxides were widely accepted to be the main mechanism of direct arsenic mobilization (31, 32). Although arsenic exists in alluvial sediments, its origin is believed to be related to the outbreaks of bedrocks (12).

To date, the globally worst-affected areas are located in Bangladesh and West Bengal (India), where arsenic in groundwater has been documented at concentrations up to 3200 μg/L (33). Moreover, in some districts of this affected area, more than 90% of tube wells were contaminated by arsenic. Inorganic arsenic concentrations in the Red River Delta of northern Vietnam have been reported between 1 and 3050 μg/L and averaged at 159 μg/L, approximately 15 times higher than the recommended value for arsenic in drinking water (16). Groundwater samples from the Upper Mekong River Basin in Cambodia displayed rather wide ranges of arsenic up to 855 μg/L for groundwater in Kandal province(26) and up to 1340 μg/L for groundwater restricted to Bassac and Mekong River (18). An arsenic concentration range of <0.1–1351 μg/L was also reported for the Lower Mekong Delta in Vietnam (29).

Weathering processes of rocks and minerals appears to be a major source of arsenic found in soils (34, 35). Because it accumulates due to weathering and translocation in colloid fractions, the arsenic concentration is usually higher in soils than in parent rocks (36). Under typical soil-forming conditions, the nature of arsenic in soil is controlled by the lithology of parent rock materials, volcanic activity, bioactivity, weathering history, transport, sorption, and precipitation (37). The average concentration of arsenic in world soil is 7.2 mg/kg (38). The concentrations of arsenic in non-contaminated soils range from 0.1 to 40 mg/kg (39). Peaty and peaty clay sediments at the depth of 7–10 m in southwest Bangladesh showed an arsenic content of 20–111 mg/kg (40). The reported arsenic ranges for sediment in the Mekong River Delta were 4–45 mg/kg (22) and those in the Red River Delta 0.6–33 μg/g (16).

Arable land can be contaminated by irrigation using arsenic-rich groundwater. It is estimated that between 900,000 and 1,360,000 kg arsenic per year was introduced into Bangladesh soil through contaminated groundwater used for irrigation (41). Assuming soil density of 1 kg/L, then irrigation water containing 0.1 mg/L of arsenic may cause a yearly increase of about 1 mg arsenic per kg soil in the first 10 cm from the soil surface (42, 43). A correlation between soil concentrations and irrigation water concentrations of arsenic was found when the age of the water-well was taken into account (42).

The concentration of arsenic in air in remote locations (away from human releases) ranges from 1 to 3 ng/m^3, whereas the concentration in urban areas may range from 20 to 100 ng/m^3 (44). Arsenic released from combustion processes generally occurs as highly soluble oxides. These particles are dispersed by the wind and returned to the earth in wet or dry deposition. Arsenic naturally occurs in coal and oil; thus, output gas from power plants may release arsenic to the atmosphere (45).

Arsenic distribution in living organisms

Arsenic is a non-essential element that is totally not required for the growth of living organisms, with the exception of a newly discovered bacterium that replaces phosphorus with arsenic for many cellular functions (46). Terrestrial plants may accumulate arsenic by root uptake from soil or by absorption of airborne arsenic deposited on the leaves (47). In general, plants growing in natural soil contain low levels of arsenic (<3.6 ppm), which is still true for plants growing on highly arsenic-contaminated soil (48, 49). Terrestrial plants growing on land bordering arsenic-contaminated waters show relatively low arsenic content, even though the sediments have arsenic concentrations as high as 200 mg/kg (50). Brake fern is the first species known as a hyperaccumulator for arsenic. Ma et al. (2001) reported a range of 1442–7526 ppm for brake fern in central Florida contaminated with CCA (chromated copper arsenate), whereas in uncontaminated sites, the range was 11.8–64.0 ppm (51). Brake fern can also hyperaccumulate arsenic deriving from insoluble forms up to 3–6 times greater than the arsenic concentration in soil. Meharg and Rahman (42) reported a positive correlation between the arsenic concentration in rice and soil. Paddy rice is more susceptible to arsenic accumulation than other cereals because of the high mobility of arsenic under flooded condition (52).

Bioaccumulation of arsenic in aquatic organisms occurs primarily in algae and lower invertebrates. An extensive study of the factors affecting arsenic bioaccumulation in two streams in western Maryland found no evidence of bioaccumulation because arsenic concentrations in organisms have an inverse relationship with increasing tropic level (53). Arsenic is mainly accumulated in the exoskeleton of invertebrates and in the livers of fish. No difference was found in the arsenic levels in different species of fish, which included herbivorous, insectivorous, and carnivorous species (44). The major bioaccumulation transfer occurs between water and algae at the base of the food chain, and this has a strong impact on the arsenic concentration in fish. Arsenic detected in fish is primarily in the organic form.

Arsenic contamination in Asia

Although arsenic exposure through groundwater is a global concern, the South and East Asia regions are the most dramatically affected. Groundwater is the main source of drinking water for many countries in South East Asia (24). An estimated 40–60 million people in South East Asia are at risk for arsenic-related health outcomes, due to elevated concentrations of naturally occurring and anthropogenic arsenic in groundwater in this region. Current data support the evidence of more than 700,000 cases of arsenicosis, and another 12.5 million cases of predicted arsenicosis in the region. Although the arsenic crisis in Bangladesh and West Bengal has been documented since the early 1990s, the elevated arsenic concentrations in the Red River Delta in northern Vietnam and in the Mekong River Delta in Cambodia and southern Vietnam have been detected only in the last 7–10 years as the demand for tube well water has increased in these regions. A significant number of residents are estimated to be at risk of chronic arsenic poisoning. The probable reason why relatively few disease symptoms had been diagnosed thus far is that arsenic-contaminated groundwater has been used for drinking water for fewer than 10 years, whereas symptoms usually become apparent 10 years or more after exposure. The contamination of groundwater by arsenic is an emerging issue in Afghanistan, Laos, Myanmar, Pakistan, and Thailand (24). Monitoring and human health assessment studies must be conducted in the region at various stages.

Rapid economic development in some Asian countries brings new challenges and creates new environmental exposure pathways to toxic substances. Economic and social changes markedly influence the daily diet, environmental exposures, and lifestyle factors in Asia. Additionally, climate change has effects on the living environment and infectious disease. With over half the world's population living in Asia, nutrition condition, environmental health threats, and changes in infectious disease rates in this region greatly affect global health.

Arsenic contamination in the abandoned mine areas: case example of South Korea—Between the early 1980s and 1990s, numerous studies have been conducted on the restoration of abandoned mine areas in countries such as Thailand, China, Poland, Britain, Spain, Portugal, France, the USA, and Canada. The oxidation process of arsenic-bearing sulfide ores has been noted as a risk factor for the release of inorganic arsenic into soil and water in the vicinity of the mine (54–58). In the past couple of years, many studies have been done on the restoration of abandoned mine areas conducted in South Korea. More than 1000 abandoned metal mines in South Korea were in operation from the early 20th century. Most metal mines in South Korea are of hydrothermal origin and were formed with regard to quartz veins. Most of these mines have ceased to function since the 1970s; yet, these mines were abandoned without any remediation efforts. During the mining operation process, mine tailings were formed from waste rocks and gangue discharged into the land surrounding the mine. For example, the Duckum Au-Ag mine, which functioned from 1935 to 1994, generated more than 870,000 m^3 of waste material. The operation of the Gubong mine from 1908–1990, one of the largest Au-Ag mines in South Korea, generated and discharged approximately 900,000 m^3 of waste materials. Fine-grained size particles like silt and clay were widely dispersed by surface runoff and wind (59). The arsenic concentration of mine tailings depends on the geochemistry and conditions present around the mine, but can range from hundreds of mg arsenic per kg (as reported in the Dongjung, Duckum, and Sanggok mines), to thousands of mg arsenic per kg (as reported in the Myoungbong, Dongil, Nakdong, and Songchun mines). The Songchun mine tailings contain the highest amount of arsenic for mine tailings in South Korea, up to 3.86%–5.87% of weight, and the average level was 4.74% (60). Cultivated soil in this area has an average arsenic level of 56.7 mg/kg (7.5–170 mg/kg), which is about 10 times higher than that of natural soil (7.2 mg/kg and also far exceeds the tolerable level of 20 mg/kg). Normally, high arsenic levels can be expectably observed in soils and groundwater surrounding the mining site, if the concentration of arsenic is very high in tailings. For the Dongjung mine area, the mean arsenic concentration in agricultural soils (97.2 mg/kg) is twice that in tailings (47.7 mg/kg), whereas a rather high arsenic concentration in tailings (8720 mg/kg) still results in very low arsenic concentration in soils (13.2 mg/kg) at the Dongil mine area (60). The former case showed reasonable evidence for other sources of enrichment, and the latter case indicated the complexity of arsenic leaching from tailings to the environment, being affected by many factors.

Arsenic can occur as one of the major components in sulfide minerals or as an isomorphous replacement for other elements in crystal lattice. Sometimes arsenic can form a solid phase with amorphous iron due to the adsorption process. When amorphous iron (Fe) transforms into crystalline phase, causing a reduction of free sites on the surface, adsorbed arsenic would be released as a result. Ahn et al. (61) reported the predominance of 56%–91% of the total arsenic presented as amorphous As-Fe phases. The extracted solution with deionized water of the tailings showed extremely low pH (2.01–3.1) and high dissolubility of arsenic (29.5 mg/L), indicating strong acidic conditions and high potential for arsenic to be released during rainfall events. Various kinds of iron and aluminum (Al) compounds have been reported to precipitate from the mine drainage, and the stream waters polluted by mining activities (62). These precipitates play an important role in the removal of heavy metals, as well as arsenic, from water by adsorption and co-precipitation.

For most Au-Ag and Pb-Zn mines, major mineral components are pyrite, sphalerite, galena, chalcopyrite, and arsenopyrite. All of these minerals can relatively contain arsenic. Arsenopyrite, however, always shows the highest level of arsenic and if found in mine tailings as one of the major components, high concentration of arsenic can be expected. Other arsenic-bearing minerals were observed at the Nakdong As-Bi mine, and extremely high arsenic levels of 4.36% and 20.2% were identified for tailings generated from the ore roasting process and the cyanidation process for gold extraction, respectively (61).

A few assessments were made of the impact of arsenic on plants in these abandoned mine areas. A poor diversity was observed at the Duckum mine tailings (63). Vegetation hardly grew on more than 80% of the total area of this site. The conclusion was that toxic substances present in soil made it difficult for plants to grow. Two species could grow normally on the tailings without any infection, but the arsenic contents were very low (0.5 mg/kg) compared with that of the arsenic hyperaccumulators, which accrue high concentrations of this element, with accumulation factors lower than 0.01. Of all the organs of these plants, usually young fronds contain more arsenic than mature ones. According to Chang et al. (63), if one person consumes 50 g of young fronds containing 0.3 mg/kg per day, the total arsenic intakes would exceed the limit of 8–14 μg per day for adults as suggested by Schoof et al. (64). The second species reported by Chang et al. (63) was the poplar tree, which has an ability to grow rapidly and survive under the circumstances of low pH and high concentrations of arsenic that are predominant on mine tailings. Mining activity is an important pathway releasing arsenic into the environment. Arsenic contamination in abandoned mine areas has a direct impact on the environment, the ecosystem, and human health.

Arsenic and human health in South East Asia

Human exposure to arsenic

From a global perspective, inorganic arsenic exposure is one of the most dangerous environmental health hazards for cancer and non-cancer outcomes. The International Agency for Research on Cancer (IARC) has classified arsenic and arsenic compounds in Group 1, which is causally associated with cancer in humans. Arsenic was also classified as Group A (human carcinogen) by the US EPA. The speciation of arsenic determines its toxicity. Inorganic arsenic, particularly the trivalent methylated species, is more toxic to human health than the organic form. The order of toxicity is AsH_3>As(III)>As(V)>MMA (monomethylarsonic acid)>DMA (dimethylarsinic acid). Arsenobetaine, arseno-choline, and arsenosugars (organic forms) are considered non-toxic.

Generally, humans can be exposed to arsenic through the following pathways: oral digestion, inhalation, and dermal contact. Daily diet, drinking water, air, dust, soil, and occupational exposure are all sources of arsenic for human exposure. Chronic inorganic arsenic exposure occurs mainly through drinking water, whereas exposure to the organic form is most commonly through seafood consumption. Exposure to elevated arsenic concentration through drinking water has affected millions of people in Argentina, Bangladesh, Cambodia, Chile, China, Ghana, Hungary, India, Inner Mongolia, Mexico, Nepal, New Zealand, Philippines, Romania, Slovakia, Taiwan, and Vietnam. The world's largest arsenic-related health issue is the contamination of drinking water source in Bangladesh and West Bengal (India), followed by the situation in Cambodia and Vietnam, where the consumption of untreated groundwater may pose a serious health threat to millions of people (7–12). In endemic regions with high arsenic exposure, drinking water is the greatest source of arsenic exposure, followed by diet. In areas without arsenic exposure through drinking water and no occupational exposure, daily diet is the main source of arsenic intake. Rice consumption would be a considerable pathway for arsenic exposure, and the risk of arsenic exposure from rice should not be underestimated (65). Taking body mass into consideration, infants and young children of all ethnicities are generally exposed to higher rice arsenic levels when compared with adults (42). Children are at higher risk of exposure because they put objects into their mouths, eat dirt, and spend more time outdoors. Additionally, children are unique in their susceptibility because of their developing organ systems, body weight, and differences in arsenic metabolism.

Occupational exposure to inorganic arsenic is a major route of exposure for metal workers and residents in the area of the smelting activity. Burning plywood treated with arsenic-bearing wood preservatives CCA (chromate copper arsenate), or dermal contact with wood treated with CCA, are routes of inorganic arsenic exposure (66). Cigarette smoke is an additional source of arsenic, but has been reported to be a small contributor based on modeling.

High doses of arsenic can cause death, but chronic lower level exposures result in serious health effects. Long-term exposure to arsenic can cause skin lesions and cancer of human organs (skin, bladder, kidney, liver, lung, and prostate). Basal cell carcinoma (BCC) and squamous cell carcinoma (SCC) are the most commonly observed cancers associated with chronic elevated arsenic exposure through drinking water. Arsenic exposure has been associated with increased risk of cardiovascular endpoints, such as hypertension, increased risk of coronary artery disease, atherosclerosis, stroke, and Alzheimer's disease, as well as diabetes (5–8). Additionally, animal studies have demonstrated that arsenic exposure can compromise the immune response. Evidence of pre-natal exposure to arsenic and alterations in gene expression measured in cord blood suggest prenatal effects. Existing evidence also shows that arsenic may have in-utero effects that can compromise fetal health, including birth weight, fetal mortality, infant mortality, intelligence, and development, especially if arsenic exposure is in concert with manganese. Although earlier work discovered the effects of co-exposure to arsenic and manganese, current studies are underway in Cambodia and Vietnam, where the concentrations of arsenic and manganese are elevated in groundwater. The impact of inorganic arsenic on human health is an area of active study.

The mechanism for arsenic carcinogenesis remains unclear, but several mechanisms have been proposed, including factors related to the biotransformation of arsenic, inhibited DNA repair, perturbed DNA methylation, cell signaling, epigenetics, oxidative stress, altered signal transduction, or initiation of growth factors or cytokines in response to arsenic exposure. When cells are exposed to DNA-damaging agents, a signal is generated such that the transcription of various genes is altered. As with many drugs, certain environmental agents do not always exhibit the same toxicity and mechanisms of metabolism. Inter-individual variation in the clearance rate and percentages of urinary arsenic metabolites have been shown through in vivo animal studies and in human populations environmentally exposed to arsenic through drinking water. Furthermore, individual differences on arsenic metabolism measured through ratios and percentages of these metabolites have been associated with increased risk of skin lesions, bladder and skin cancers, and hypertension in humans.

Diet and other co-factors in arsenic exposure

Further study is in needed to fully understand the modifying factors that account for the variability in disease risk observed in countries affected by inorganic arsenic in drinking water. Established factors that influence the susceptibility of arsenic-related health outcomes include diet (67–77), gender, age, environmental co-exposures (63,64), smoking (65), betel nut use (67), sunlight (UV) (78–83), and genetics (84–87). Individuals living in the Red River Delta, Vietnam, have a lower incidence or absence of arsenic-related health outcomes due to the use of sand filtration and other factors of the population (13). Manganese exposure has been documented in Cambodia as well as in Bangladesh. Other unique co-factors should be well characterized in epidemiologic and geochemical studies.

Nutritional status is known to influence the ability to metabolize arsenic based on early animal studies and most recently based on population studies (88). Variation in the metabolism of arsenic may be associated with the risk of arsenic-related disease endpoints, and therefore the connection to diet is very important. A study conducted in Bangladesh found that dietary protein, methionine, and cysteine were associated with a significantly greater excretion of total urinary arsenic (88). As described previously, ratios of urinary metabolites have been associated with increased risk of hypertensions, skin lesions, and bladder or skin cancers. Recent dietary studies demonstrated that increased intake of cysteine, methionine, calcium, protein, and vitamin B12 were associated with lower percentages of urinary inorganic arsenic and higher primary methylation ratios (urinary MMA-to-InAs). The elevated consumption of niacin and choline was associated with higher secondary methylation of inorganic arsenic (DMA-to-MMA ratios) (89). Similar studies conducted in a USA population showed that protein-deficient individuals excreted a higher amount of ingested InAs than MMA (90). Additional cooking practices should be well understood so that additional sources of inorganic arsenic can be considered in exposure assessment.

Conclusions

Researchers have been identifying the impact of arsenic on the environment and the threat to human health. Naturally occurring in bedrock, arsenic might be introduced into various environmental components – sediment, soil, water, and air – resulting in serious environmental contamination. Subsequently, arsenic can be incorporated into the food chain and readily enters the human body. This review has summarized the remarkable results concerning arsenic contamination of aquifer, soil, and air, as well as useful information about the negative effects and potential risks of arsenic exposure. Adequate attention was paid to the impact of arsenic on the abandoned mine-tailing ecosystem. Finally, the situation of abandoned mine tailings showed the consequence of the lack of attention during and after mining processes, and therefore, proved the necessity of sustainable development. Clearly, environmental impact assessment, restoration, and management of the ecosystem in the mine areas during and after mining exploitation are of great importance.

Geochemical differences in groundwater, economic ability to sustain remediation efforts and other factors make the mitigation of inorganic arsenic unique for each region affected by inorganic arsenic in groundwater. Recent UNICEF estimates are that one-fifth of the tube wells in the Mekong Delta in Vietnam have arsenic concentrations greater than safe drinking water standards (10 μg/L) (17, 91). In addition to the elevated arsenic concentration in the Red River Delta, naturally occurring levels of iron concentrations aid arsenic mitigation through the use of sand filtration (17). The sand filtration method is effective in the Mekong Delta due to the elevated iron concentration, with arsenic concentrations reduced to below 50 μg/L in the majority of instances and many reduced below the WHO guideline of 10 μg/L (92). However, the iron levels are much lower in the Mekong Delta, and the reduction of arsenic by the sand filtration is less effective (91). Varying water compositions worldwide, and even within a country, highlight the need for unique mitigation strategies. Socioeconomic and cultural practices, the presence of dissolved organic matter and microorganisms in groundwater, as well as the feasibility of sustainable water treatment options require unique study for each region affected by elevated concentrations of inorganic arsenic in groundwater (91). A recent paper discusses the differences between arsenic mitigation in Bangladesh and Vietnam based on differences in geochemical features and available resources, and this scenario would also be true for other emerging regions including Cambodia, Myanmar, Thailand, Pakistan, Afghanistan, and others (80). These are areas for further study as the data are less plentiful compared with Bangladesh and Vietnam. Human activity has an impact on the biogeochemical and hydrologic processes that govern the inorganic arsenic release to groundwater. Interdisciplinary efforts to better characterize the transport of arsenic and reactants that facilitate the release of arsenic are important for human health studies (93).

A need exists to develop a better coordination between local and global data compilation on health effects and disease etiology for vulnerable populations. Moreover, an epidemiologic global effort is needed to fill gaps in our understanding of the relationship between arsenic exposure and disease in subgroups of the population, including children. A better understanding of timing of exposure and susceptibility to arsenic-related disease is necessary. Understanding the mechanisms of interactions between arsenic and infectious diseases is important, as well as environmental co-exposures that are unique to each region and the interaction between arsenic and genetic makeup to understand the predisposition to disease and to develop prevention in those regions. The entire environmental exposure pathways and the vulnerable subgroups of the populations, including cultural practices, should be considered when designing interventions to improve public health. In addition to public health care and prevention, we must develop remediation technologies that are sustainable in the communities affected by arsenic. Specifically, focus must be placed on removal efficiency and the economic impact on the communities.

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