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Technological Role in the Development of Arsenic Contamination in Minerals and Its Purification: A Systematic Literature Review

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Abstract: *Arsenic pollution is a long term international environmental and human health issue that is linked to natural geological, mineral and ground water and industrialization processes. Arsenic is in a natural form as sulphide minerals like arsenopyrite, pyrite and galena, which are normally found in geologic deposits in relation to metallic minerals. Even though geochemical natural processes contribute to the low levels of arsenic in the soils and groundwater, technological activities associated with mining, mineral processing, agriculture, and industrial production have increased the rate of release into the ecosystems (Bundschuh et al., 2021; Wang et al., 2021). Arsenic pollution has therefore become a very common environmental problem in developed and developing parts of the world.*

There has been a vast literature on the environmental and health effects of arsenic contamination especially in areas where groundwater has become the major source of drinking water (Rahman et al., 2020). Exposure to water contaminated with arsenic has been known to lead to severe health diseases such as arsenicosis, cancer, cardiovascular disease and neurological diseases that arise due to long-term exposure (Kumar et al., 2024). These dangers show the significance of considering natural and technological factors that determine arsenic mobilization in the environmental setting.

The literature review combines multidisciplinary research data on historical background of arsenic contamination, natural and human sources of arsenic in mineral, technological influences on arsenic mobilization, regional patterns of contamination, and purification technologies in arsenic-contamination remedial efforts. The review highlights the two-sidedness of technology as a source of contamination but the next-generation of remediation (Liu et al., 2024). The improvement of analytical techniques of detection, adsorption systems, membrane filtration, and biological remediation techniques have enhanced the management of arsenic, but the application of these methods still faces challenges in developing areas (Frisbie and Mitchell, 2022).

The research reveals gaps in the literature related to integrated remediation technologies, sustainable mining procedures, and purification systems that are scalable, and interdisciplinary teamwork is needed to mitigate the risks of a global exposure to arsenic.

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Introduction

Arsenic pollution is generally regarded as one of the most complicated issues of environmental pollution that can be related to mineral resources and ground water systems. Arsenic is a naturally occurring metalloid that occurs in the crust of the earth and is usually present in sulphide minerals like arsenopyrite, pyrite, and galena (Pikinini, 2022). These minerals are often linked with those of metal ores such as gold, copper and lead and as such, arsenic contamination is strictly coupled with geological formations and mineral mining operations. Despite the fact that the mobilization of arsenic is a process of nature, the technological advancement led to an enormous increase in the lack of exposure to the environment, the formation of arsenic in the soil and in the water system due to the growth of technologies (Wang et al., 2021).

This has been caused by industrialization, mining, and agricultural intensification that has resulted in massive arsenic contamination of soils, surface water, and underground waters (Bundschuh et al., 2021). Mining and smelting activities subject arsenic carrying minerals to oxygen and water, which facilitates oxidation processes that give out soluble arsenic compounds to the environment (Nordstrom, 2011). Pollution may have been caused by agriculture in the past through the application of arsenic-containing pesticides and through the use of contaminated groundwater to irrigate crops (Ghosh, 2021). These technological activities have relegated the local occurrence of arsenic contamination to a global environmental health concern in both developed and developing regions (Manisalidis et al., 2020).

Contamination of groundwater in Bangladesh and India is one of the most dangerous environmental health crises associated with arsenic exposure. The presence of arsenic in drinking water has been exposed to millions of people as a result of groundwater production in arsenic-bearing aquifers (Rahman et al., 2020). The issue arose when the tube wells were sunk to make drinking water safe against microbes, which accidentally caused release of arsenic in layers of the sediment to the ground water systems (Ahmed et al., 2004). Long-term exposure to contaminated arsenic water has been considered to have diverse impacts on health such as arsenicosis, cancer, cardiovascular disease, neurological disorders, and developmental issues (Kumar et al., 2024; Saha and Rahman, 2020). These health effects illustrate the high relationship between environmental contamination and technological development on the health of the population.

The international level of arsenic pollution has stimulated the creation of interdisciplinary research methods. The study of Arsenic contamination now involves the fields of environmental science, hydrology, mineral engineering, toxicology, and the health of the population as well as water treatment technology (Guo et al., 2024). Environmental scientists study geochemical characteristics of arsenic in the soils and aquifers, and mineral engineers study the application of mining technologies in the mobilization of arsenic. Toxicologists and other researchers working in the field of public health examine the biological impacts of exposure to arsenic and the engineers devise methods of purifying the water supplies that are tainted with arsenic. This multi-disciplinary response is indicative of the multi-facetedness of the arsenic contamination as an environmental and technological problem.

Knowledge of the role of technology in mobilization and purification of arsenic is crucial in maintaining sustainable environment management. Technological cycles may be a source of contamination, as well as find a solution by collectivity detecting, monitoring, and remedial systems (Liu et al., 2024). As the world keeps on consuming mineral resources and groundwater, there is also a possibility of increased chances of contamination by arsenic unless there are preventive strategies in place.

This review of the literature focuses on the technological contribution to the arsenic contamination of minerals and the analysis of purification technologies invented to eliminate the contamination. The review is a synthesis of research on arsenic contamination patterns over the years, geological sources, anthropogenic factors, technology of arsenic release, regional trends of contamination as well as methods of remediation. The review will incorporate the findings of various disciplines in order to give a detailed knowledge on arsenic contamination and the technological means they can employ to control the problem.

History of Arsenic Poisoning

Since time immemorial, human communities have employed Arsenic in the fields of medicine, pigments, cosmetics, and preserving actions (Chenet et al., 2023). The ancient Egyptians employed arsenic compounds in embalming due to their preserving and antimicrobial properties, whereas to the Greek and Roman civilizations arsenic was a part of dyes, medical preparations and metallurgy. These initial uses show that arsenic was appreciated because of its chemical and other physical specifics. But even though it was common, the early societies were not scientifically informed of the toxicological consequences of arsenic exposure in the long-term. Consequently, one tended to use arsenic without proper knowledge on its effects to the environment and human beings.

The awareness of arsenic poisoning was slow to develop because cases of poisoning were observed in Europe in the eighteenth and nineteenth centuries (Alsukaibi, 2022). Arsenic was referred to as the king of poisons because it was colorless and tasteless and was therefore hard to detect in food and drinks. Early chemists and medical practitioners started looking into the arsenic poisoning and developed the toxicology and detection techniques in a forensic manner. These achievements helped in the initial awakening of regulatory consciousness and influenced governments to start checking the applications of the harmful chemical elements. The development of toxicology as a scientific field in this period was a step in the right direction towards knowledge of the health hazards of arsenic exposure.

Mining and smelting activities that were boosted during the Industrial Revolution contributed to a rise in the quantity of contaminated arsenic (Oliver et al., 2020). The fast industrialization gave rise to more mining of metal ores, most of which consisted of arsenic-bearing minerals like arsenopyrite and pyrite. The mining of sulphide ores subjected these minerals to oxygen and water, which increased the rate of oxidation of these minerals releasing arsenic into the nearby environments (Chaudhary et al., 2024). Smelting plants also released significant amounts of industrial emissions that polluted the atmosphere arsenic that was ultimately deposited into the soil and water systems. These advancements in technology transformed the magnitude of environmental pollution of arsenic to different levels that were not prevalent in past times.

The use of arsenic-based pesticides in agriculture in the nineteenth and twentieth century led to the long-term contamination of soil (El-Ghiaty and El-Kadi, 2021). The Paris Green and other compounds have been widely used to control pests in agriculture hence resulting in build-up of arsenic remnants in the soils of farmlands. Arsenic in these pesticides leached into ground water systems and as a result of run off, it was transported to ground water over time. Environmental exposure pathways were increased because of industrial applications of arsenic in pigments, wood preservatives, and chemical production (Shooshtarian and Hosseini, 2021). These uses showed that although technological innovation was useful towards industrial and agricultural productivity, it might unintentionally cause environmental contamination hazards.

By the middle of the twentieth century, arsenic poisoning had turned into an environmental and public health issue on the international level (Browne and Raff, 2023). In scientific research the association of exposure to arsenic and chronic diseases such as cancer, cardiovascular diseases, and neurological damage was identified. The development of environmental chemistry and research into public health was able to detect and monitor arsenic in the water and soil systems through improved detection. To regulate the exposure level of arsenic, governments and international bodies started to develop safety standards and regulatory frameworks.

The historical analysis also proves that the development of technological progress has not only aggravated the polluting of the environment with arsenic but also sparked the scientific knowledge of the environmental toxicology. Although the industrial and agricultural technologies increased the release of arsenic, they facilitated the creation of analysis techniques, environmental laws, and cleaning technologies that remain current in the arsenic management approaches.

The Arsenic found naturally in geological sources.

The natural geological processes are the main source of arsenic pollution of the environment. Arsenic is a naturally occurring metalloid that occurs in the crust of the earth and it is usually related to the mineral deposits that are formed by geological and geochemical processes. It is transported to the surrounding ecosystems by processes like oxidation, weathering, volcanic processes, geothermal narrative, and interactions among sediments and water (Raju, 2022;

Smedley and Kinniburgh, 2002). These natural routes add up to be a founder of baseline levels of arsenic in the soils, sediments and groundwater systems in most parts of the world. Knowledge of these processes is necessary to differentiate between the arsenic contamination as a result of the natural processes and the aggravated contamination by human activity. In most settings, groundwater contamination with arsenic is an indication of geochemical exchanges between water and minerals, over a long period, and not a result of direct anthropogenic contamination (Nordstrom, 2011).

Some of the most crucial sources of natural arsenic contamination are sulphide minerals, including arsenopyrite (FeAsS), pyrite (FeS 2), and galena (PbS) (Bundschuh et al., 2021). Such minerals are usually observed in geological structures related to the deposits of various metals such as gold, copper and lead. Arsenic can also be present in the sedimentary rocks, volcanic deposits, and hydrothermal mineral systems (Pikinini, 2022). The arsenic-bearing minerals on exposure to oxygen and water undergo chemical reactions which liberate arsenic into the environment. During the oxidation process, arsenic is transformed to soluble oxides (arsenate (As 5 +) and arsenite (As 3 +) that may move through groundwater networks and poison drinking water sources (Yasasve et al., 2022). Relative mobility and toxicity of these forms are sensitive to the environmental conditions like redox potential and pH. Arsenite is more toxic and mobile, e.g., than arsenate in water (Smedley and Kinniburgh, 2002).

This natural displacement of arsenic commonly takes place in long geological time periods but still has potential risks on the ecosystem and human population residing in arsenic-infested areas. In sedimentary water, arsenic can be discharged due to the reductive dissolution of the iron oxyhydroxides, where microbes cells decrease iron mineral and cause release of the arsenic adsorbed to the groundwater (Ahmed et al., 2004). This process is generally known as a significant source of arsenic at groundwater in deltaic and floodplains settings. These geochemical reactions show interactions among the microbial activity, mineral composition, and groundwater chemistry in determining the mobility of arsenic processes in the natural systems.

Climate and geological factors that cause weathering are other factors that contribute to the mobilization of arsenic (Guo et al., 2024). Weathering of the rocks and minerals occurs chemically, emitting arsenic to the soils and water catchment systems. Areas with high rainfall, high temperatures and high hydrological cycles are those that are likely to have high rates of weathering and thus there is the probability of arsenic being liberated (Smedley and Kinniburgh, 2002). Under the severe weathering in the tropical and subtropical environment, the resulting sediments may contain high amounts of iron oxides that fix the arsenic and ultimately release the arsenic under varying geochemical conditions. Arsenic may build up in time in sedimentary basins and alluvial aquifers and dissolve in groundwater in particular geochemical conditions, including low-oxygen conditions or varying levels of pH (Guo et al., 2024). These natural cycles provide the reason as to why a level of similarity in the level of industrial activity may still lead to different geological risks posed by arsenic in different regions of the world.

Another source of arsenic contamination in the environment is volcanic eruptions and geothermal systems (Morales-Simfors et al., 2020). Arsenic as a gas, ash, and aerosol is emitted into the atmosphere by the volcanic activities and may subsequently settle on the land and water surfaces. These deposits can have an introduction of arsenic in the systems of soil and water coverages within extensive geographical regions. On the same note, geothermal waters are usually rich in high levels of arsenic since the hot water reacts with rocks that are rich in arsenic in the deep underground (Nordstrom, 2011). Geothermal fluid can also cause arsenic to enter into the aquatic ecosystems and drinking water sources when they surface via hot springs or groundwater ways. The processes become especially important in tectonically active areas that are also volcanic and geothermal, including sections of Southeast Asia, South America, and East Africa (Morales-Simfors et al., 2020).

Hydrogeological conditions are also significant in regulating the arsenic mobility. The flow patterns of groundwater, their sediment composition, and microcrust activity affect the process of remaining of arsenic by minerals or its dissolution in water (Ahmed et al., 2004). Geochemical conditions and arsenic distribution may change due to changes in the groundwater level, natural floods, and deposition of sediments. The dynamic processes described show the complexity of natural systems of arsenic contamination and the significance of the monitoring of these systems at long-term periods.

Though the natural geological processes form the baseline levels of arsenic in the environment, excessive contamination is usually caused by the contact between the natural processes with human activities (Bundschuh et al., 2021). As an illustration, geochemical conditions may be changed by groundwater extraction, mining activities, irrigation activities, and land-use modifications, which increase the rate of mobilization of arsenic (Nordstrom, 2011). Groundwater pumping in the deep aquifers can bring oxygen to the bottom of layers of sediment or alter redox conditions and intensify the release of arsenic. In the same way, any disturbance of the land (related to agriculture or construction) may put the arsenic-bearing sediments in the state of weathering.

Thus, natural arsenic contamination is supposed to be perceived as a component of a larger system of the environment where the geologic processes and human activities can interact to affect the degree of contamination. It is important to realize that natural geological sources are crucial to the formation of effective monitoring plans and to the establishment of remediation technologies that would be appropriate to the environmental conditions of a certain area. The geochemical processes that regulate the movement of arsenic can help the researchers and policy makers differentiate the natural contamination and anthropogenic contributions to enhance the environmental management measures.

Manmade sources of Arsenic poisoning.

Human activities are major contributors to extensive contamination of arsenic compared with the background levels because they hasten the movement of arsenic in mineral deposits and increase other forms of contamination in the environment. The combination of industrialization, mineral mining and agricultural activity, and industrial processes has resulted in an increased concentration of arsenic in the soils, water systems, and the atmosphere (Bundschuh et al., 2021; Wang et al., 2021). Although arsenic is a naturally found element in various geological formations, technological activities usually disturb such geological formations modifying geochemical conditions and making arsenic more mobile. Due to the persistent increase in the world's need in the supply of mineral resources and agricultural production, anthropogenic sources of arsenic pollution are one of the primary environmental issues (Manisalidis et al., 2020).

One of the most essential human-made sources of arsenic pollution is mining, and it is well-known among other activities (Daraz et al., 2023). A wide variety of useful metal ores, such as gold, copper and lead, are linked to sulphide minerals that are naturally rich in arsenic. When mining is being done, the mineral is exposed to water, oxygen, and chemical reagents, which hasten the emittance of arsenic into the adjacent ecosystems (Lottermoser, 2010). Surface mining, underground excavation and processing of the ore all lead to disruption of the arsenic-bearing geological materials. The arsenic levels in waste rock piles and tailings that are produced during the mining process are usually very high, and they pose a significant potential contamination in the long-term unless they are handled (Nordstrom, 2011). In many countries throughout the world, such as North America, South America, Europe, and Asia, mining-related arsenic contamination has already been reported, which proves the worldwide scope of the problem (Bundschuh et al., 2021).

The main role in the arsenic mobilization in the mining environment is acid mine drainage (AMD). The sulphide mineral oxidation, in particular, pyrite oxidation and arsenopyrite oxidation, results in sulphuric acid, which decreases the pH of the surrounding water bodies and elevates the solubility of arsenic and other hard-toxic metals (Khan et al., 2022; Wang et al., 2024). Arsenic is more mobile under acidic conditions and may be transported in the system of groundwater and surface water. This may be sustained many years after mining activities have been discontinued particularly in the discarded mining sites where waste products are subjected to the environment (Younger et al., 2002). Acid mine drainage thus is one of the most intractable sources of anthropogenic arsenic pollution, which may take long-term environmental management/remediation measures.

Arsenic contamination is also caused by smelting activities. As part of the extraction of high-temperature metals in ores, arsenic can be emitted into the atmosphere in the form of PM and gas emissions (Shockley, 2021). These airborne arsenic products may go a long way before landing on the land and water surfaces and pollute agricultural soils, rivers, and lakes (Kar, 2022). The emissions that are caused by the smelting plants can hence extend the arsenic contamination within a vast geographical location, and this can exploit ecosystems beyond the source of origin. The past industrial smelting processes in the industrialized parts of Europe, North America, and Asia have resulted in long-term environmental pollution that still impacts on soil and water quality (Dudka & Adriano, 1997). Contaminated soils and sediments might still secrete arsenic into the ecosystems around the smelting facilities even after the facilities are closed.

The agricultural activities as well have contributed to the contamination of arsenic especially with the past use of arsenic pesticides and arsenic based fertilizer. During the nineteenth and twentieth centuries, lead arsenate and other similar compounds were popular in the food industry to eliminate pests and enhance crop yields (Mallareddy et al., 2023). The chemicals lead to the build-up of arsenic in the soils of the farms where it may be experienced over decades. The use of the groundwater contaminated by arsenic also worsens the situation and adds arsenic into crops and soil systems due to irrigation (Ghosh, 2021). In other areas, it has been indicated that rice farming is a route through which arsenic is taken into the food chain posing even more health hazards to the human population (Zhao et al., 2010). The fact that agricultural activities lead to the pollution of the ground water indicates that food production systems may be connected to environmental exposure to arsenic.

Semiconductor manufacturing, glass manufacturing and chemical processing are industrial manufacturing processes that generate other contamination pathways (Cai et al., 2024). Electronic parts, metal alloys and special chemicals are some of the uses of the arsenic compounds and poor waste management leads to polluting the environment through wastewater or atmospheric emissions (ATSDR, 2007). The rapid industrialization in the developing world has raised the issues relating to the level of arsenic pollution caused by manufacturing processes especially in areas whereby the ability to put in place adequate regulations and waste-treatment facilities are minimal.

The anthropogenic pollution of arsenic can be widespread even after the industrial processes are stopped because of the chemical stability and persistence of arsenic in the environment (Li et al., 2021). Arsenic may result in sediments, soils, and groundwater systems; thus, generating long-term contamination problems. Historical mining, agricultural, and industrial production still persists to pollute the ecosystem and people globally (Nordstrom, 2011). Arsenic may be strongly bound to soil particles and mineral surfaces and as a result, it can be difficult to remove contamination even after the source of pollution has been eliminated. The continued occurrence makes it difficult to remediate and enhance the significance of preventive environmental management practices.

Hence, human actions not only contribute to the release of arsenic to the environment but also makes the remediation process difficult because they leave behind long-term contamination that can last decades or even centuries. To tackle anthropogenic arsenic contamination, thus, a complex of better industrial methods, environmental surveillance mechanisms, and environmentally friendly remediation technologies are needed (Bundschuh et al., 2021). It is important to comprehend the effects of technological processes on the mobilization of arsenic in order to minimize the environmental risks and safeguard human health.

Geographic Areas of Arsenic Contamination.

The level of arsenic contamination in different geographic areas differs considerably because of the variations in geology, industry, hydrology, and water use (Shaji et al., 2021). These geographic differences indicate how complicated the interaction between natural geochemical processes and technological progress of humans is. In certain areas, natural geological features are the main causes of arsenic contamination, whereas in other areas, industrial and farming processes aggravate the issue. These regional trends will be important in understanding how to create effective monitoring strategies and remediation technologies to suit local environmental conditions (Smedley and Kinniburgh, 2002). The variations in the composition of the aquifers, sediment chemistry, and the dynamics of groundwater flow may be an effective cause of arsenic mobility and distribution in the environmental systems (Guo et al., 2024).

South Asia is one of the worst-contaminated regions of arsenic across the globe (Rahman et al., 2020). Bangladesh and arsenic-bearing minerals in alluvial aquifers in the Bengal Delta region which comprises of Bangladesh and West Bengal, India have led to widespread contamination of groundwater in the region. Drinking water and irrigation of arsenic through ground water extraction has also mobilized arsenic in sediment layers into aquifer system through reductive action of dissolution (Ahmed et al., 2004). The groundwater is the major source of water to millions of people in this region, and therefore the risk of exposure to arsenic contamination is a key issue in terms of public health. Research has attributed long-term exposure in the area to arsenicosis, cancer, cardiovascular disease, and developmental disorders (Saha and Rahman, 2020; Kumar et al., 2024). The case of South Asia shows that natural geological factors together with the extensive use of groundwater and the growth of the population can lead to the development of the acute environmental health crises.

North and South American mining areas have also been subjected to long-term arsenic pollution which is related to mining operations (Bundschuh et al., 2021). The arsenic contamination in the southwest of the United States and some regions of the Andes Mountains in South America is associated with both the geological formations and mining activities (Nordstrom, 2011). Gold, copper and other metal are commonly extracted out of ores that have arsenic-bearing sulphide minerals. Waste mining, tailings and acid mine drainage have also led to the contamination of the surrounding soils and water bodies (Lottermoser, 2010). Contamination is present in most of the cases even after mining activities have been abandoned showing the long-term effects of mining technologies on the environment. Arsenic contamination still persists in old mining districts of countries like Chile, Peru, and the United States because of old mining wastes and abandoned mines (Bundschuh et al., 2021).

Southeast Asian and African volcanic and geothermal areas also have a high concentration of arsenic in the groundwater systems (Irunde et al., 2022; Ng’ethe and Jalilinasrabady, 2024). Geothermal waters in tectonically active areas react to arsenic-bearing rocks at the very depth of the ground, which leads to the naturally high levels of arsenic in groundwater (Morales-Simfors et al., 2020). Natural processes can present a problem in ensuring the safety of drinking water in many countries that are located along the volcanic belts or geothermal zones. As an illustration, the geothermal springs and volcanic aquifers located in some regions of Southeast Asia have been found to be causing arsenic pollution to the local water systems (Shaji et al., 2021). Likewise, the arsenic-contaminated areas in the eastern part of the African continent, in the East African Rift Valley, are also based on volcanic geology and geothermal activity whereby the arsenic in water comes in contact with volcanic sediments and hydrothermal fluids

(Ng'ethe and Jalilinasrabady, 2024). The extracted groundwater and population increase can increase these naturally high levels of arsenic.

Such patterns of regional contamination show that the interaction between natural geology and technological development takes place. Although geology creates baseline levels of arsenic, human actions including groundwater abstraction, mining, farming, and industry manufacturing usually enhance pollution (Smedley and Kinniburgh, 2002). The degree of exposure of arsenic is also affected by regional variations in climate, hydrology, and economic development. As a result, arsenic contamination should be perceived as the geographically differentiated phenomenon that needs the contextual solutions. The successful management measures require the application of a combination of geological understanding, technologic advancement, environmental surveillance and community policy to deal with arsenic pollution in various parts of the world (Manisalidis et al., 2020).

Arsenic release is also affected by technical factors arising due to technological advances.

Mining and mineral processing are the technological processes that greatly contribute to the mobility of arsenic in the natural environment (Wang et al., 2021). As arsenic is naturally found in most mineral deposits, the current mining methods expose arsenic-containing minerals to environmental factors that trigger chemical reactions and release of the contaminants. The emergence of the large-scale mining and the sophisticated mineral processing methods have increased the efficiency of resource extraction but have elicited threats on the environment, which is contaminated by the presence of arsenic-bearing ores (Lottermoser, 2010).

One of the technological factors that cause the arsenic mobilization the most is open-pit mining since it subjects great amounts of sulphide-rich rock to oxygen, water, and weathering (Arthur-Holmes et al., 2022). In the excavation process, overburden and ore materials which carry arsenic-bearing minerals like arsenopyrite are brought up to the surface where they are subjected to oxidation reactions. The result of these reactions is solubic compounds of arsenic which may find their way into surrounding soil and water systems. The mining activities that are conducted open-pits tend to produce waste rocks and tailings in large volumes and, therefore, there is a high risk of contamination in the long-term when the waste materials are not managed properly (Younger et al., 2002). Also, surface mining has the potential to change local hydrological systems which can increase the movement of arsenic into groundwater and river systems.

The underground mining also enhances the mobilization of arsenic by dewatering activities and exposing the surfaces of the mineral to the groundwater systems (Cacciuttolo & Atencio, 2023). To ensure safe operational conditions in underground mines, dewatering is needed, however, the pumping of groundwater mined tunnels can carry dissolved arsenic into nearby aquifers. Underground mining activities also permanently change the patterns of groundwater flowing, thereby accelerating the proliferation of arsenic contamination in the long term (Nordstrom, 2011). These mechanisms demonstrate the potential of technological interventions in underground environments to change geochemical situations unintentionally and increase the motion of contaminants.

The mineral processing methods (flotation, roasting, crushing, and smelting) produce arsenic-containing tailings, emissions, and wastewater (Whitworth et al., 2022). The crushing and grinding of the ore exposes more surface area to arsenic and therefore, the mineral arsenic-bearing minerals become more prone to oxidation. The valuable minerals and the waste materials are separated by using the flotation processes, although in most cases they are not able to remove the tailings of arsenic. Arsenic can be released into the atmosphere through the release of gaseous emissions or particulate matter by roasting and smelting processes that involve the treatment of ores at high temperatures (Dudka & Adriano, 1997). Such emissions can be subsequently accumulated in the soil and bodies of water, which will offer other contamination routes.

Tailings storage forms a major environmental issue in the mineral processing practice. Poor tailings management may cause permanent soil, sediment, and groundwater system contamination (Gupta et al., 2022). The waste materials in tailings dams and storage facilities are usually on fine forms and contain arsenic and other heavy metals. In case these structures break or are not well taken care of, there is a possibility of release of contaminants into nearby ecosystems. In tailings, even in cases where the tailings facilities are structurally sound, arsenic can still be released over prolonged periods of time even when there are slow chemical reactions in the stored materials (Lottermoser, 2010).

Besides the direct contamination routes, technological mining operations can also cause changes in local geochemical environments, which determine the mobility of arsenic. The chemical form of arsenic and its movement in water systems may change due to changes in pH, redox potential and microbial activity (Nordstrom, 2011). As an illustration, acidic environment caused by the oxidation of sulphide minerals enhances the solubility and motility of arsenic, pitting the environment at a greater challenge to regulate. These geochemical processes prove that the contamination of arsenic related to the mining is not merely the effect of the exposure to minerals but rather the result of the complicated environmental interactions caused by the technological processes.

In general, the literature proves that in the mobilization of arsenic, mining and mineral processing technologies are extremely critical. Although these technologies play a crucial role in the extraction of resources and economic growth, they pose environmental threats that are supposed to be managed. Sustainable mining, enhancing tailings management system, and environmental monitoring technology are hence required to minimize the arsenic contamination with the activities of mining of minerals (Younger et al., 2002; Wang et al., 2021).

Procedures of Arsenic purification.

Advances in technology have made giant strides in sensing and managing arsenic, especially following increased concerns on the presence of arsenic in the environment especially ground water and soil. With the developments of environmental monitoring technologies, it is now possible to measure arsenic in very low levels, which has enhanced risk assessment and the management of contamination. Inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) are some analytical techniques that can accurately monitor the levels of arsenic in the body of water, soil, and biological samples (Bacon et al., 2024; Smedley and Kinniburgh, 2002). These methods are very sensitive and accurate and allow scientists and environmental organizations to determine the origin of contamination and monitor the dynamics of arsenic levels in the environment. The construction of portable detection and field-testing kits has further enhanced the monitoring power especially in remote and resource constrained regions (George et al., 2012).

Technologies of water purification have also improved considerably, providing a variety of solutions to arsenic in the polluted water sources. Some of the most commonly investigated systems include adsorption systems, coagulation filtration, membrane filtration, and ion exchange (Liu et al., 2024). One of the most frequently used methods is adsorption due to its relatively low costs and the simplicity of the operations. Activated alumina, iron oxides and biochar are some of the materials that have shown effectiveness in the removal of arsenic in water (Mohanty, 2017). Iron adsorbents are also very effective since under the right chemical conditions, arsenic attaches firmly to surfaces of iron hydroxide.

Another commonly used method of purification is coagulation-filtration especially in the municipal water treatment plants. It is achieved by adding coagulants, e.g., ferric chloride or alum, which make arsenic precipitate and create particles to be filtered out (Sorg et al., 2014). Reverse osmosis and nanofiltration membrane filtration technologies are very effective in the removal of dissolved arsenic species though they may be very energy consuming and expensive to maintain (Shih, 2005). Arsenate ion can also be eliminated by ion exchange systems whereby the ion is replaced by less harmful ion on the resin materials.

In addition to the traditional treatment solutions, there has been development of biological remediation systems which are seen as viable solutions to sustainability. Phytoremediation involves the application of plants that absorb arsenic in the soil or water systems and minimizes the pollution by the natural biological mechanisms (Al Hamedi et al., 2023; Ali et al., 2013). Some plant species like the Pteris vittata (Chinese brake fern) are known to accumulate arsenic in their tissues and as such, they are also of use in cleaning the environment. Some of the microbial remediation methods include bacteria and other microorganisms that convert arsenic to less harmful or less mobile forms using biochemical reactions (Oremland and Stolz, 2003). Such biological methods are especially appealing due to the fact that they need less energy and may be implemented in the areas that are sensitive to the environment.

Filtration-based and low-cost adsorption-based community-level systems have also been invented to solve the problem of arsenic in rural and low-income areas (Frisbie and Mitchell, 2022). As an example, arsenic-contaminated South Asian regions have adopted household filtration systems that use iron-coated sand, or locally available material. Such systems are readily available to the communities without centralized water treatment systems. It has been revealed that locally made systems of filtration can greatly decrease the exposure to arsenic provided that they are well maintained and monitored (Ngai et al., 2007).

Although significant advances have been made in terms of technology in arsenic remediation, a number of challenges still exist. Purification systems are usually effective depending on the chemistry of water, the capacity of maintenance, and the financial resources (Smedley and Kinniburgh, 2002). The remediation processes in a lot of developing areas have low chances of being sustained in the long term, because of lack of infrastructure and expertise. Technological innovation in the purification of arsenic is therefore still concerned with the endeavors of creating cost effective, scalable and environmental friendly solutions that can be applied in various geographical and socioeconomic settings.

Research Gap

Although much has been conducted on arsenic contamination and the remediation technologies, there are a number of critical gaps in the literature. Current literature has made much progress in the study of the chemical behavior of arsenic, environmental distribution, and purification methods available; a combination of these research spheres is, however, scarce. Among the key gaps, there is no critical research that would study mineral processing technology, contamination routes, and remediation methods in one concept (Wang et al., 2021). A significant portion of the existing literature presents arsenic contamination as a geochemical issue or a water-treatment issue, but does not provide an adequate discussion of the long-term environmental contamination of the environment by the decisions made in technological use in the mining and mineral processing sector. These two views must be combined to come up with preventive strategies aimed at minimizing the amount of arsenic released into the environment instead of using down stream remediation.

The other gap of vital significance is associated with scaling and availability of the arsenic purification technologies, especially to the rural and low-income populations. Although laboratory-based tests show a high removal efficiency of adsorption substances, membrane filtration systems, and ion exchange technologies, such alternatives tend to demand technical skills, a regular maintenance system, and financial resources that are not likely to be present in the affected areas (Liu et al., 2024; Smedley & Kinniburgh, 2002). In most regions of South Asia, Africa, and Latin America, the cost of water treatment systems is decentralized and it may have to rely on the available resources, so the long-term sustainability becomes a challenge (Rahman et al., 2020). Even though community-scale filtration systems, locally made adsorbents are promising, more studies are required on their ability to withstand over time, cost-effectiveness, and culture acceptance under practical environments (Ngai et al., 2007). In the absence of the scalable solutions, technology that is being developed in arsenic removal could remain inaccessible to those who are most affected by contamination.

In the literature, preventive mining technologies are also not discussed as much as research focused on remediation (Dehkordi et al., 2024). The majority of studies focus on the ways of eliminating arsenic in the contaminated water or soil after the contamination has been introduced. Nonetheless, there are less studies that aim at transforming mining activities to reduce the amount of arsenic that is emitted during mining and mineral treatment. The sustainable mining practices including enhanced waste containment, process of oxidation, and purposeful tailings management are underresearched fields (Lottermoser, 2010). Treatment of arsenic at the point of origin may have a great impact on both the long-term environmental hazards and the treatment cost. Such imbalance in research priorities indicates the necessity to focus on technological innovation which could result in prevention, instead of primarily remediation.

The other notable gap is connected to the low level of integration of interdisciplinary studies between environmental engineering, mineral processing, and public health (Manisalidis et al., 2020). Arsenic pollution is both a nature problem and a social-economic and a health problem to the people. Most of the studies are based on either environmental chemistry or health outcomes without linking these two areas fully. As an illustration, the studies of groundwater pollution in most cases fail to consider societal variables, including water-use practices, infrastructure constraints, or policy implementation issues (Frisbie and Mitchell, 2022). On the same note, mineral engineering research can be done on the efficiency of extraction without taking into account the long term environmental and health effects. Interdisciplinary cooperation is thus a must to the development of comprehensive strategies of managing arsenic which consider not only the technological aspect of the contamination but also the societal aspect.

Another area that is poorly developed in research is long-term monitoring of remediation technologies. Numerous remediation techniques are considered in controlled laboratory tests or short-term field experiments, and fewer studies consider their efficacy during a long period (Sorg et al., 2014). Changes in groundwater chemistry, climatic variability and maintenance of infrastructure are some of the environmental factors, which can affect the long term functionality of purification systems. Longitudinal studies are hard to carry out without because one would want to know whether or not remediation technologies are effective in the long term. To fill these gaps in research, there is need to move towards the integrated interdisciplinary and sustainability-oriented methods of managing arsenic contamination. Scalable purification technologies, preventive mining, and long-term monitoring of the environmental systems should be considered in future studies. The gap between mineral processing, environmental engineering and the study of public health can be minimized to help scholars and policymakers create a more effective way of reducing the problem of arsenic contamination and safeguarding the vulnerable groups.

Conclusion

The literature proves that arsenic contamination of minerals is caused by the interactions between the natural geological processes and technological processes of industrial development. There are natural geochemical processes, such as mineral weathering, volcanic activity, and interactions between groundwater and rocks, which contribute to the baseline level of arsenic in the soils and water systems (Raju, 2022; Morales-Simfors et al., 2020). Nonetheless, the development of industrialization and mining activities has boosted the magnitude and severity of arsenic emissions to the ecosystem greatly. The movement of arsenic in mineral deposits into water systems (groundwater and surface water) and the atmosphere has been increased by mining, smelting, agriculture, and industry (Bundschuh et al., 2021; Wang et al., 2021). Such technological practices have made the issue of arsenic contaminations no longer a local geological issue but a global environmental and community health problem.

Arsenic is also not easy to manage as it is environmentally persistent. When emitted to the soils, sediments, and aquifers, arsenic may have a long shelf life, because of its chemical stability and capacity to adsorb to the surface of the minerals (Li et al., 2021). Such persistence causes a long-term risk of ecosystem and human population contamination, especially in areas where groundwater forms the major drinking water (Rahman et al., 2020). Consequently, the problem of arsenic contamination is still a major problem to environmental management and protection of human health across the globe.

Simultaneously, the advancement of technologies has made it possible to create detection, purification, and remediation technologies that could help reduce the risks of arsenic contamination. Developments in the fields of analytical chemistry, such as inductively coupled plasma mass spectrometry and atomic absorption spectroscopy, have enhanced the process of tracking arsenic pollution in the environmental systems (Bacon et al., 2024). Large scale water treatments such as adsorption systems, coagulation filtration processes, membrane filtration, and ion exchange methods have been found to be effective in the elimination of arsenic in polluted water supply (Liu et al., 2024). Other solutions like phytoremediation and microbial remediation offer environmentally friendly solutions that can supplement the traditional treatment methods (Al Hamedi et al., 2023). The illustrated developments demonstrate the two-sided nature of technology in contributing to contamination as well as offering remedies to manage the environment.

Although these are the developments, there are still large gaps in the translation of technological innovation into sustainable and accessible arsenic management approaches. Some purification technologies involve financial resources, technical skills, and infrastructure which might be unavailable in developing areas where the arsenic pollution is worst (Frisbie and Mitchell, 2022). Also, preventive strategies that can lessen the emission of arsenic during mineral mining have not been studied as extensively as remediation-oriented studies (Dehkordi et al., 2024). The effective solution to the pollution of arsenic thus cannot be achieved only through technological innovation, but through better environmental regulation, enforcement of the policy and community participation.

Future studies ought to concentrate on integrated remediation systems that are multi-purpose in detection, treatment as well as monitoring of the environment. There should also be priorities on sustainable mining technologies that would reduce the mobilization of arsenic at the source. Besides this, creation of readily available purification procedures applicable in rural and low-resource based communities is also critical towards minimising chances of arsenic exposure around the globe. Multidisciplinary cooperation of environmental scientists, mineral engineers, researchers of public health, and policymakers will play a vital role in the further development of such activities (Manisalidis et al., 2020). The future studies have the potential to help decrease the concentration of arsenic and safeguard the environment and human lives by enhancing technological innovation and sustainable environmental management practices.

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