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Opinion

Arsenic Contamination Needs Serious Attention: An Opinion and Global Scenario

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Abstract: Arsenic (As) contamination is a serious global concern, polluting our natural resources, including water and soil, and posing a danger to the environment and public health. Arsenic is present in the groundwater of several countries and this contaminated water is used for irrigation, drinking, and food preparation, which poses the greatest threat to public health. Nearly 106 countries are affected by groundwater arsenic contamination and an estimated 230 million individuals worldwide are exposed to its adverse health effects, including increased cancer risks, associated cardiovascular disease and diabetes, skin lesions, neurological effects, kidney damage, and foetal or cognitive-development-related complications. Arsenic is highly toxic and ranked first in the priority list of ATSDR (Agency for Toxic Substances and Disease Registry, 2022) and among the 10 chemicals of major public health concern on the World Health Organization (WHO) list. The maximum permissible level of arsenic in drinking water has been established at 10 μg/L by WHO, as well as by the Environmental Protection Agency (EPA) and European Union (EU). These regulatory standards underscore the gravity of the problem, and actions to prioritise the development of effective detection, mitigation strategies, and collaborative initiatives are necessary. This opinion article covers (i) arsenic footprints—global scenario and impact, (ii) awareness and education and (iii) mitigation approaches (detection and removal strategies) and future perspectives, which collectively will help in controlling and preventing As contamination of our global water resources. Regulatory and legislative bodies and development agencies are crucial for raising awareness and countering this alarming concern by implementing collaborative actions to protect our environment and public health and to provide safe drinking water for all.

Keywords: arsenic contamination; toxic; water; soil; environment; public health; global awareness; regulations and mitigation strategies

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1. Introduction

Arsenic (As) contamination is a serious growing global concern affecting our natural resources and public health. As-contaminated water is used for irrigation, drinking, and food preparation, which poses a great threat to public health. Arsenic exists in both organic and inorganic forms, each with distinct implications on human health. Inorganic arsenic is of particular concern due to its toxicity, and exposure primarily occurs through drinking water and food products [1]. Understanding the sources and pathways of arsenic contamination is crucial for devising effective mitigation strategies. The primary contributors to inorganic arsenic exposure are drinking water and various food items [2,3]. In the context of drinking water, natural sources often contain arsenic at levels below 1–2 μg/L. However, the risk escalates significantly in regions where groundwater serves as a prevalent source of drinking water. Arsenic concentrations can surge in such groundwater, particularly in areas characterised by sulphide mineral deposits and sedimentary formations from volcanic rocks [4,5]. Variations in the characteristics of certain regions create conducive environments for elevated arsenic levels. Volcanic rocks and associated geological formations can release arsenic into groundwater, leading to contamination [6]. In areas with sulphide mineral deposits, the interaction between minerals and water can mobilise arsenic, further exacerbating the contamination issue. This intricate interplay of geological factors highlights the complexity of addressing arsenic contamination.

The elevated toxicity of arsenic manifests in a spectrum of severe health complications, underscoring the urgency in addressing its widespread contamination. Arsenic exposure has been linked to the development of various cancers, including skin, kidney, liver, bladder, and lung-related cancers [7]. Furthermore, the impact extends beyond cancer, contributing to the prevalence of cardiovascular diseases, diabetes, and neurological issues among affected populations [8]. The detrimental consequences also encompass complications in foetal and cognitive development, raising concerns about long-term health effects on vulnerable populations. Recognising the severity of arsenic contamination, authoritative bodies such as the World Health Organization (WHO), Environmental Protection Agency (EPA), and European Union (EU) have established stringent guidelines to mitigate exposure. These organisations have set a maximum permissible level of arsenic in drinking water at 10 μg/L [9]. This regulatory standard is designed to safeguard public health by minimising the risk of arsenic-related ailments associated with water consumption. Exceeding the established permissible levels poses grave health implications, as an uncontrolled intake of arsenic-contaminated water heightens the risk of the aforementioned health conditions. This underscores the importance of comprehensive strategies and collaborative efforts to address not only the contamination itself but also the broader public health challenges posed by arsenic.

Arsenic contamination remains a critical global issue, with its adverse effects extending across vital natural resources and public health. The toxic nature of arsenic amplifies its threat to communities worldwide, particularly when found in water sources designated for irrigation, drinking, and food preparation. Recent data indicate that as of 2022, arsenic contamination has become a widespread crisis, affecting groundwater in a staggering 106 countries. This far-reaching problem has exposed an alarming 230 million people to the detrimental effects of arsenic exposure, significantly contributing to a global public health emergency [10,11]. The impact is not uniform, with certain regions grappling more intensely with the challenges of safeguarding the well-being of their populations in the face of arsenic-contaminated water sources. Highlighting the gravity of the situation, arsenic holds a prominent position on the 2022 priority list of the Agency for Toxic Substances and Disease Registry (ATSDR) [12]. The ATSDR prioritisation underscores the urgent need for comprehensive interventions to mitigate the impact of arsenic contamination on human health. Simultaneously, the WHO has classified arsenic as one of the top 10 major public health concerns worldwide [4]. This recognition from a leading global health authority further emphasises the imperative for international collaboration to address the complex challenges arising from arsenic contamination and its far-reaching consequences for both human health and the environment.

The gravity of the situation underscores the need for urgent action to prioritise the development of effective detection and mitigation strategies. Collaborative initiatives involving global regulatory bodies, legislative bodies, and development agencies are essential for raising awareness and addressing this alarming concern, ensuring the protection of the environment, public health, and the provision of safe drinking water worldwide. The issue of arsenic contamination in drinking water led to a pivotal regulatory change by the EPA in January 2001 [13]. In response to growing concerns about the health risks associated with arsenic exposure, the EPA revised the standard for acceptable arsenic levels in drinking water, reducing it from the previous standard of 50 μg/L to a more stringent limit of 10 μg/L [14]. This adjustment reflects a commitment to safeguarding public health by minimising the allowable concentration of arsenic in drinking water sources.

The absence of explicit recognition for the right to access arsenic-safe drinking water and uncontaminated food in key international declarations highlights a critical gap in addressing a pressing global health issue. Notably, the Universal Declaration of Human Rights, a foundational document articulating fundamental human rights, does not explicitly address the specific right to be free from exposure to harmful levels of arsenic in water and food [15]. Similarly, the 2030 Sustainable Development Goals (SDGs), a comprehensive framework adopted by the United Nations (UN) member states, lack a specific target addressing arsenic contamination [16]. This oversight is significant considering the impact of arsenic on public health and its potential to undermine progress towards various SDGs, including those related to health, clean water, and poverty alleviation. UNESCO, with its mission to promote international collaboration in the fields of education, science, and culture, has not explicitly prioritised the issue of arsenic contamination. This oversight comes despite the multidisciplinary nature of arsenic research, which spans geological, environmental, and health-related dimensions.

The field of arsenic studies encompasses a broad spectrum of disciplines, including geological, geochemical, biological, environmental, technological, and social aspects [17]. Despite the multifaceted nature of arsenic contamination, research in this domain is often fragmented, and integrated, comprehensive approaches are relatively rare. This fragmentation has led to gaps in our understanding of the intricate interactions between geological formations, environmental factors, and human health in arsenic-affected areas [18]. Public and stakeholder awareness is a critical component, influencing community response, policy advocacy, and the success of interventions. Despite these diverse areas of study, there is a notable lack of integrated and coordinated global initiatives. Existing regulations are often criticised for being either highly stringent, leading to unnecessary treatment costs, or too permissive, resulting in elevated arsenic exposure with subsequent health and societal repercussions. Striking the right balance requires collaborative efforts that comprehensively bring together researchers, policymakers, and communities to develop effective, evidence-based solutions that address the complex challenges posed by arsenic contamination [19,20].

To address this gap, it is imperative for organisations like the UN and UNESCO to proactively engage in collaborative efforts with a diverse network of scientists, professionals, and researchers. Establishing an international platform dedicated to the exchange of knowledge and experiences related to arsenic research is pivotal. This concerted effort is not only essential for advancing scientific knowledge but also for shaping policies and interventions that safeguard the right to access arsenic-safe drinking water and uncontaminated food, thereby promoting the well-being of communities worldwide.

2. Global Status and Impact (Continent-Wise)

2.1. Origins of Arsenic Contamination

Arsenic exists in the environment in both organic and inorganic forms, commonly found in oxidation states of −3 (arsenides), +3 (arsenites), and +5 (arsenates and organoarsenic compounds) [21]. While natural processes like rock weathering and volcanic activity contribute to arsenic release, human activities significantly exacerbate the global arsenic issue. The different sources of arsenic production and subsequent contamination and their categorisations have been succinctly presented in Figure 1.

2.1.1. Anthropogenic Sources

Anthropogenic sources of arsenic contamination stem from human activities and industrial processes, significantly contributing to environmental and public health concerns. There are multiple sources that can be classified under the anthropogenic category, some of which have been highlighted below:

1. Mining and smelting: These processes can release large amounts of arsenic into the air and water, contaminating ecosystems present nearby and posing health risks to communities residing in proximity to such activities [22].

- Tailings and waste disposal: Improper disposal of mining waste and tailings can lead to the release of arsenic into surrounding environments, exacerbating contamination.
- Airborne dispersal: The airborne dispersion of arsenic during mining and smelting operations poses a threat to air quality and can contribute to widespread environmental contamination.

2. Industrial effluents: Industrial processes, including the production of chemicals, metals, and semiconductors, can discharge arsenic-containing wastewater into rivers and streams, presenting a serious global concern [23].
   - Unregulated discharge: Lack of proper regulations and treatment facilities can result in uncontrolled discharge of arsenic-containing effluents, exacerbating the contamination of water bodies.
   - Cumulative impact: The cumulative impact of multiple industrial activities in a region can significantly amplify the overall arsenic burden in aquatic ecosystems.
3. Coal combustion: Burning coal for energy production releases arsenic into the air, significantly contributing to the severe contamination of water, soil, and environmental resources [24].
   - Coal ash disposal: Improper disposal of coal ash, containing concentrated arsenic, poses a direct risk to soil and water resources, leading to prolonged contamination.
   - Atmospheric deposition: Arsenic released into the air during coal combustion can undergo atmospheric deposition, further contaminating terrestrial and aquatic environments.
4. Agricultural practices: The use of arsenic-based pesticides and herbicides in agriculture stands out as a major source of soil and water contamination, especially in regions with intensive agricultural activities [25].
   - Runoff and leaching: Arsenic-based chemicals in agriculture can contribute to soil contamination through runoff and leaching, impacting water quality in nearby water bodies.
   - Residue accumulation: Persistent accumulation of arsenic residues in soils, resulting from prolonged agricultural use, poses a continuous threat to crop quality and human health.

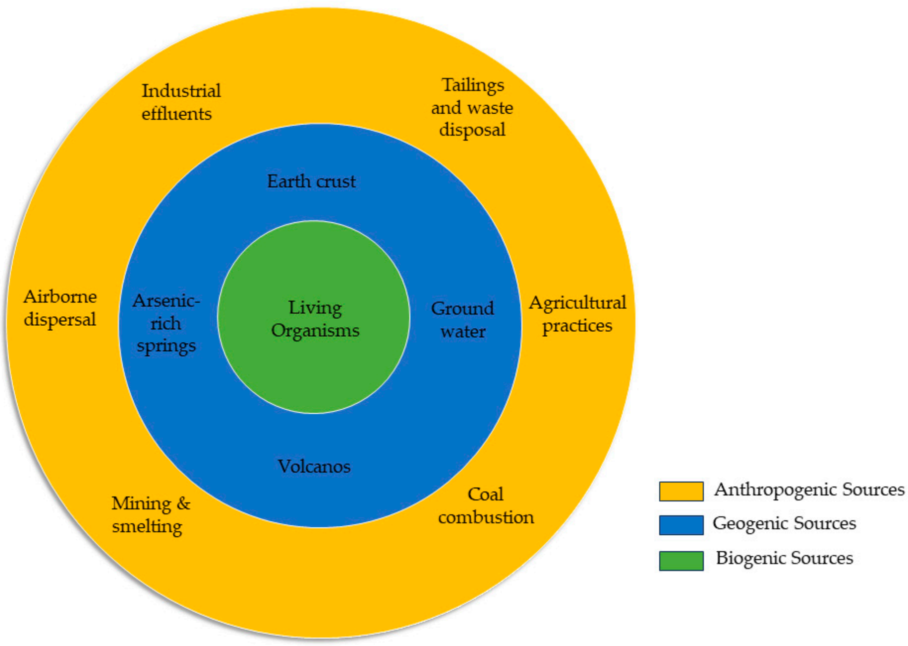

Figure 1. Major sources of arsenic contamination and three main categories contributing to arsenic contamination.

2.1.2. Geogenic Sources

Geogenic sources of arsenic contamination originate from natural geological processes, where arsenic is released into the environment without direct human intervention. Geogenic arsenic contamination poses a significant challenge, particularly in regions where communities rely heavily on groundwater for drinking purposes. The following are the two main components with geogenic origins:

- Geographical variability: The prevalence of arsenic in groundwater exhibits geographical variability, with certain regions being more susceptible to natural arsenic contamination [26].
- Hydrogeological factors: Hydrogeological conditions, such as the presence of certain minerals and the type of aquifers, play a crucial role in arsenic mobilisation in groundwater [26].

2.1.3. Biogenic Sources

Biogenic sources of arsenic contamination are associated with living organisms and natural biological processes. For instance, certain bacteria can transform arsenic from less toxic forms to more toxic forms, contributing to groundwater contamination. Additionally, the decay of organic matter in soil and sediments can release arsenic into the environment [27]. Although biogenic sources are typically overshadowed by geogenic and anthropogenic sources, they play a crucial role in the overall arsenic cycle and environmental impact.

2.2. Impacts of Arsenic Contamination

The following systems are interrelated and ultimately arsenic contamination affects our environment, soil, and water resources, which subsequently has adverse effects on animal and human health [28].

2.2.1. Environmental Ramifications

Arsenic accumulation profoundly impacts ecosystems, soil, and aquatic life.

- Biodiversity loss: The disruption of ecosystems due to arsenic accumulation can lead to biodiversity loss, affecting various plant and animal species.
- Food chain contamination: Arsenic entering aquatic environments can contaminate the food chain, with potential cascading effects on higher trophic levels.
- Long-term soil effects: The persistence of arsenic in soil can have enduring effects, affecting the long-term productivity and health of terrestrial ecosystems.

2.2.2. Health Impacts on Humans

Chronic exposure to arsenic poses a serious health concern, especially in regions where contaminated groundwater serves as the primary drinking water source. Long-term exposure is associated with various health problems [29]:

- Residential proximity: Communities residing in close proximity to arsenic-contaminated water sources face a higher risk of chronic health issues due to prolonged exposure.
- Vulnerable populations: Children, pregnant women, and individuals with compromised immune systems may be more vulnerable to the adverse health effects of arsenic exposure.
- Mitigation challenges: Implementing effective mitigation measures is challenging, especially in resource-limited regions, exacerbating the health risks associated with arsenic contamination.

2.3. Continent-Wise Breakdown of Arsenic Contamination

Figure 2 provides a comprehensive visualisation of the areas affected by arsenic contamination across the globe, highlighting the extent of this critical problem ($\geq$10 μg/L) [30]. Table 1 further presents a breakdown and list of countries grappling with arsenic contamination and the size (%) of the populations affected. These data underscore the urgency of addressing arsenic contamination on a global scale, considering the severity and level of this problem [11,31]. Although it seems like a problem localised in Asia, the supply chain among countries can facilitate the spread to other countries quickly if proper measures and actions are not taken in a timely manner.

Table 1. Number of countries affected by arsenic contamination in groundwater in each continent (≥10 μg/L) and the proportions of the areas and populations affected. Information source Ref. [31].

Continent	Countries Affected	Proportion of Globally Affected Areas	Proportion of Total Global Affected Population
Asia	31	64%	94%
South America	9	14%	1.6%
North America	11	10%	0.6%
Africa	20	9%	3.7%
Oceania	4	2%	0.01%
Europe	31	1%	0.2%

2.3.1. Asia

Arsenic contamination is a grave concern in Asia, where 31 countries have been found to be severely affected. The proportion of the affected population globally is 94% (contributed to majorly by Asia) and millions of people are exposed to high levels of arsenic in their drinking water, mainly due to naturally occurring contamination. This has resulted in severe health crises, with widespread cases of arsenic-induced skin lesions and a heightened risk of various cancers [32,33]. The Asian countries which are highly affected include, but are not limited to, the following:

- Bangladesh: Bangladesh is one of the countries most severely affected by arsenic contamination. Millions of people in rural areas depend on groundwater for drinking and a high amount of naturally occurring arsenic has led to widespread health problems [33].
- India: Arsenic contamination is a concern in several Indian states, particularly in the Ganges-Brahmaputra delta region. West Bengal and Bihar are among the worst affected areas. Arsenic contamination in communities across India has surged by ~145% in the past seven years [34]. Also, arsenic contamination has been reported in some districts of Uttar Pradesh, Punjab, Assam, and Jharkhand.
- Vietnam: Some regions in Vietnam, including the Mekong Delta, have reported arsenic-contaminated groundwater, posing a risk to the population's health.

Figure 2. Global occurrence of arsenic reported in major countries/regions with arsenic concentration ≥ 10 μg/L. Reprinted from Ref. [30], Copyright (2021), with permission from Elsevier.

2.3.2. South America

As listed in Table 1, nine countries are affected. Some of the severely affected countries are as follows:

- Argentina: Around four million individuals in Argentina are exposed to excessive amounts of As in their drinking water. Elevated amounts (>1000 μg/L) of As have been identified in the Chaco-Pampean Plains and Cuyo sections of the Andes, which are located in the country's centre and northwestern regions, respectively [35].
- Chile: Arsenic contamination is also prevalent in parts of northern Chile, with contaminated areas in regions such as Atacama and Antofagasta, primarily linked to mining activities. It poses environmental risks to local ecosystems and underscores the importance of responsible mining practices.
- Bolivia: Bolivia faces arsenic contamination challenges in regions with a history of mining, such as the Cerro Rico mountain in Potosí. The mining of silver, tin, and other minerals has resulted in arsenic pollution in soil and water. Furthermore, industrial activities and agricultural practices contribute to arsenic contamination in various parts of the country.
- Peru: Arsenic contamination in Peru is a significant concern in mining regions such as the Andean highlands and the Amazon rainforest. The extraction of copper, gold, and other minerals has led to the release of arsenic into the environment. Additionally, informal gold mining operations, known as artisanal and small-scale gold mining (ASGM), contribute to arsenic pollution in soil and water [36,37].

2.3.3. North America

Eleven countries have been shown to be affected. The most notable countries include the following:

- The United States: Arsenic contamination is not as widespread in the U.S., but certain areas, such as parts of the American Southwest, have reported elevated arsenic levels in groundwater, mainly due to geological factors. Historically tied to mining activities in Western U.S. states like Arizona and California, arsenic pollution has affected both water sources and local communities, highlighting the importance of stringent regulations and ongoing remediation efforts in the USA, where over 2 million people use drinking water from private wells with As concentrations exceeding the regulatory limit of 10 μg/L [38,39]. Approximately 7% of the sampled wells exhibited arsenic concentrations surpassing the maximum contaminant level (MCL) of 10 μg/L. Notably, the southwest region raised the most substantial concern, with approximately 16% of the tested drinking water wells surpassing the MCL for As concentration [40].
- Canada: In Canada, regions such as British Columbia and the Yukon Territory have grappled with arsenic contamination due to mining operations, necessitating vigilant monitoring and mitigation measures. Despite being geographically limited, these contamination cases emphasise the need for continued environmental protection and public health initiatives in affected areas. The Canadian government has implemented measures to monitor and mitigate arsenic pollution in the affected areas.

2.3.4. Africa

Arsenic contamination poses a significant health risk in parts of Africa, where 20 countries are affected [41]. The notable affected regions are as follows:

- Nigeria: Arsenic contamination has been reported in some regions of Nigeria, particularly in the northwestern part of the country. This contamination is often associated with the presence of arsenic-rich geological formations.
- Ethiopia: Some areas within Ethiopia, especially in the Great Rift Valley region, have experienced arsenic contamination in groundwater.

- Tanzania: Arsenic contamination has been reported in various parts of Tanzania, including the Dodoma area and other regions with geological conditions conducive to arsenic release into groundwater.

2.3.5. Europe

While Europe is relatively less affected by arsenic contamination compared to other continents, pockets of contamination have been observed in 31 countries. The sources of contamination can vary, including industrial and agricultural activities. These localised issues highlight the need for continued monitoring and remediation efforts [3,42–44]. The most affected ones are as follows:

- Hungary: Hungary has faced arsenic contamination issues in groundwater sources, primarily in the northeastern region.
- Romania: Arsenic contamination in Romania has been a concern, particularly in regions with a history of mining, such as Maramureș, and due to incidents like the Baia Mare cyanide spill in 2000 [45]. Efforts to address contamination include stricter regulations and remediation measures in affected areas.
- Croatia: Arsenic contamination in Croatia's part of the Pannonian Basin is notable in regions with historical mining activity, such as Sisak-Moslavina County. Additionally, industrial zones around cities like Osijek and Vukovar face arsenic pollution challenges. Efforts are underway to remediate contaminated sites and promote sustainable agricultural practices to reduce arsenic inputs in these areas.
- Serbia: Serbia's part of the Pannonian Basin, particularly around the Bor mining complex in eastern Serbia, faces significant arsenic pollution due to historical mining activities. Industrial zones in cities like Belgrade and Novi Sad also contribute to arsenic contamination in soil and water. Remediation efforts and improved industrial waste management practices are being implemented to address arsenic pollution in these regions [46].

2.3.6. Australia

Arsenic contamination is a concern in Australia, primarily associated with mining and industrial activities. Contaminated areas include parts of Western Australia, South Australia, and Queensland, where mining operations have released arsenic into the environment, affecting both surface and groundwater sources. Effective environmental management and timely stringent regulations are crucial for addressing this problem and protecting the well-being of communities.

2.3.7. Antarctica

Antarctica remains the least affected continent due to its sparse human population and limited industrial activities. However, even in this pristine environment, researchers have detected trace amounts of arsenic contamination [47]. These findings emphasise the importance of continued environmental monitoring to preserve the unique ecosystems of Antarctica.

3. Detection and Removal Methods

3.1. Detection Methods

Ensuring the precise identification and quantification of arsenic levels holds paramount importance in establishing safety standards for drinking water and selecting appropriate arsenic removal technologies, alongside the implementation of effective mitigation measures. Many detection techniques, spanning chromatographic, spectroscopic, colorimetric, biological, electroanalytical, and coupled methods, have been developed over the years, with some capable of detecting arsenic at concentrations lower than the WHO-recommended limit of 10 µg/L. Although our recently published review article [10] provides comprehensive insights into these analytical methods, many existing approaches are predominantly suitable for laboratory settings, proving expensive and time-intensive. Consequently, these methods may entail high capital costs, rendering them impractical for the routine analysis and monitoring of extensive sample sets. To address these limitations, there is a growing need for swift, reliable, portable, and cost-effective methods, particularly on-site sensor-based technologies, to facilitate efficient arsenic detection and removal. For a concise overview of various methodologies for arsenic detection and determination in drinking water, refer to Figure 3 [10] and Table 2 [10,48–50].

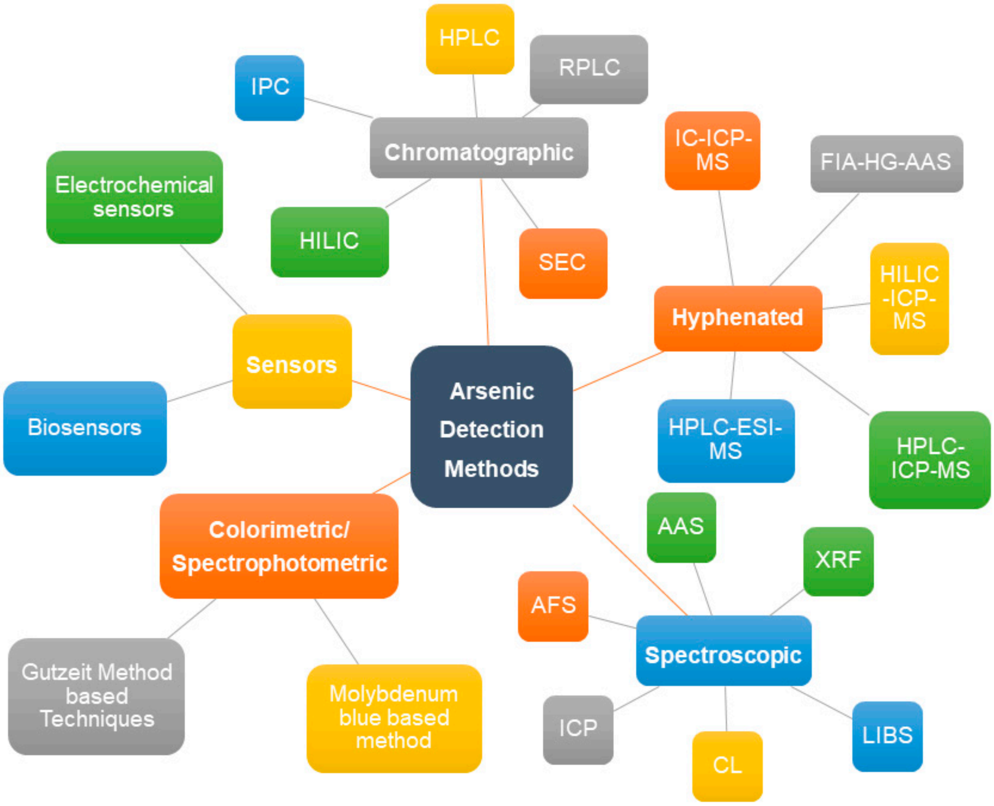

Figure 3. Various analytical techniques and methods for arsenic detection and determination [10]. Reprinted from Ref. [10], Copyright (2023), with permission from the Royal Society of Chemistry.

Table 2. Summary of different types of arsenic detection techniques [10,48–51].

Method	Principle	Detection Range	Cost	Time Required	Advantages	Disadvantages
AAS	Absorption of arsenic-specific wavelengths	1 µg/L to 1 mg/L	Moderate	Minutes	High sensitivity and specificity	Requires specialised equipment
ICP-MS	Ionisation and mass analysis	0.1 µg/L to 1 mg/L	High	Minutes	Exceptional sensitivity and accuracy	Expensive, complex, and time-consuming
HPLC	Separation and quantification	1 µg/L to 1 mg/L	Moderate	Minutes to hours	Can separate various arsenic species	Complex instrumentation and setup
XRF	Excitation and detection of X-ray emissions	1 mg/L to 100 mg/L	Moderate	Seconds	Non-destructive; useful for solid samples	Limited to bulk sample analysis
Colorimetric sensors	Chemical reaction and formation of coloured change	1 µg/L to 1 mg/L	Low	Minutes	Portable and easy to use	Limited to qualitative or semi-quantitative results

Table 2. *Cont.*

Method	Principle	Detection Range	Cost	Time Required	Advantages	Disadvantages
Electrochemical sensors	Detection via electrochemical reactions (using different types of nanomaterials)	1 µg/L to 1 mg/L	Low to Moderate	Minutes	Portable, rapid results, and low cost	May require electrode maintenance
Biosensors	Use biological components for detection	1 µg/L to 1 mg/L	Variable	Minutes	High specificity and potential for multiplexing	Limited to specific biological components, may require maintenance

AAS: atomic absorption spectroscopy; ICP-MS: inductively coupled plasma mass spectrometry; HPLC: high-performance liquid chromatography; XRF: X-ray fluorescence.

3.2. Extraction Methods

Various arsenic removal techniques, ranging from traditional to innovative approaches, are deployed to combat arsenic contamination in water sources. Conventional methods like coagulation–flocculation, sedimentation, and granular media filtration are widely employed, effectively eliminating arsenic by entrapping particles or facilitating their settlement [52]. In the realm of innovation, advanced oxidation processes (AOPs) leverage chemical reactions to degrade arsenic compounds, while nanotechnology-based methods utilise nanostructures for efficient adsorption. Hybrid systems, amalgamating multiple techniques, are gaining traction for heightened arsenic removal efficiency. Although these newer methods boast potential advantages, including increased efficiency and reduced maintenance requirements, ongoing research and practical application are imperative to affirm their scalability, cost-effectiveness, and long-term reliability in ensuring access to safe drinking water for affected communities. For a concise overview of common arsenic removal methods from water, refer to Table 3 [52–55].

Table 3. Summary of some common arsenic removal techniques [52–55].

Method	Description	Advantages	Disadvantages
Coagulation and filtration	Addition of coagulants to form flocs and remove arsenic by filtration.	Effective for both As(III) and As(V), relatively low cost, and suitable for large-scale treatment.	Requires regular maintenance and monitoring of coagulant dosing; produces sludge that requires proper disposal.
Adsorption	Use of adsorbent materials to capture arsenic on their surface.	Highly effective, relatively low operational costs, and can be used at both point-of-use and point-of-entry.	Limited capacity of adsorbents; requires periodic regeneration or replacement.
Ion exchange	Use of ion exchange resins to exchange arsenic ions with other ions in the resin.	Highly effective for both As(III) and As(V); suitable for both small-scale and large-scale systems.	Requires regeneration or replacement of ion exchange resins; release of regenerant chemicals needs proper management.
Reverse osmosis (RO)	Use of a semipermeable membrane to remove arsenic and other impurities by forcing water through the membrane.	Highly effective at removing arsenic; suitable for small-scale treatment and point-of-use systems.	Relatively high operational costs, generates wastewater, and requires maintenance of the RO system.
Sedimentation	Allowing particles to settle out of the water after coagulation–flocculation.	Low cost and simple.	Requires sufficient settling time.

Table 3. *Cont.*

Method	Description	Advantages	Disadvantages
Electrocoagulation	Passing an electric current through water to destabilise and coagulate arsenic particles.	Effective for both arsenic(III) and arsenic(V), reduced sludge production compared to conventional coagulation, and has potential for automation.	Requires electricity, maintenance of electrodes, and appropriate monitoring and control.
Biological treatment	Use of specific bacteria to convert arsenic from soluble to insoluble form for removal.	Can be environmentally friendly and cost-effective.	Slower treatment process; requires specific conditions and careful monitoring.
Solar oxidation and precipitation	Oxidise arsenic using sunlight and remove it by coagulation or filtration.	Low-cost method with minimal chemical use.	Weather-dependent; may require longer contact times.
Zero-valent iron (ZVI)	Use of zero-valent iron media to reduce and adsorb arsenic from water.	Effective for As(V) removal. Relatively low-cost technology.	Limited efficacy for As(III) removal, making pre-oxidation necessary. Maintenance and replacement of iron media.

4. Mitigation Approaches and Future Perspectives

Addressing the global arsenic problem requires a multifaceted approach, encompassing preventive measures, remediation, and control strategies. Some key approaches include the following:

4.1. Education and Public Awareness

Raising awareness about the contamination and risks of arsenic exposure and promoting safe water practices are crucial. Global collaboration and awareness among academics, local communities (public), and development agencies will lead to sustainable solutions to mitigate the problem and alleviate socioeconomic, environmental, and public-health concerns. Basic training programs and governmental initiatives should be conducted to teach communities about arsenic contamination, water testing, and overall awareness about the importance of reporting the problem so that the necessary action can be taken. Furthermore, promoting safe water handling and storage practices at the household level helps to reduce exposure to arsenic. The importance of water as a valuable and essential resource for all lives on the planet should be highlighted using online social platforms and forums. Environmental education must be a compulsory part of primary education (globally) to understand the importance of precious natural resources.

4.2. Safe Water Supply Provision

Providing access to safe drinking water sources is an essential need. Communities affected by arsenic contamination often require alternative sources, such as deep tube wells or piped water systems. Promoting safe water practices, such as using alternative water sources and installing arsenic removal filters, is necessary.

4.3. Management of Agricultural Practices

Agricultural practices play a significant role in arsenic contamination, particularly in regions where arsenic-contaminated water is used for irrigation. Crop selection and rotation can be optimised to minimise arsenic uptake by plants, with a focus on selecting crops that naturally need less water, e.g., rice vs. grains or pluses. Compounds such as arsenic trioxide, lead arsenate, and cacodylic acid were once widely employed for their pesticidal properties in crop protection. Despite a decline in their use, residues persist in soil and water, posing ongoing risks to human health and ecosystems. Mitigation efforts include promoting alternative pest control methods, phasing out arsenic-based pesticides, implementing soil remediation techniques, and enforcing stringent regulations to safeguard against further contamination. Promoting organic farming practices that avoid or reduce the use of pesticides and fertiliser that contains arsenic can further mitigate contamination risks. Farming education and government support and regulation would help in controlling the arsenic-associated (or similar) contamination problems [56,57].

4.4. Innovative Approaches Applied to Extraction

Various technologies (summarised in Table 3) have been developed to remove arsenic from water sources, including coagulation–filtration, adsorption using materials like activated carbon, and membrane-based methods like reverse osmosis, etc. Continued research into effective arsenic detection and mitigation technologies is vital to address the challenge. Innovations in arsenic removal approaches are vital, with an emphasis on exploring low-cost and sustainable methods suitable for regions with limited resources. Innovative approaches, such as the use of nanomaterials or adsorbents specifically designed with filters for arsenic removal, would be helpful in advancing removal and treatment technologies. Future mitigation efforts are envisaged to benefit from advancements in water quality monitoring, including remote sensors, real-time data collection, advanced IoT (Internet of Things), and data analytics. This would enable more efficient and proactive monitoring of arsenic levels, allowing for timely action. Global collaborative R&D initiatives are required to solve global problems.

4.5. Regulatory Measures and Controls

Regulation plays a pivotal role in addressing arsenic contamination. Governments and regulatory bodies need to continuously review and apply stringent controls and actions. Additionally, policies and protocols should focus on groundwater management and land use practices to prevent arsenic from entering water sources in the first place. Robust regulatory frameworks will also enable accountability and ensure that the responsible parties are held liable for addressing contamination issues. By implementing and enforcing appropriate regulations and policies, governments can safeguard the health and well-being of their populations, promote sustainable water management practices, and mitigate the long-term impacts of arsenic contamination. Enhanced enforcement mechanisms, including penalties for non-compliance, will be necessary to deter violations and maintain water quality. Future regulations should incorporate educational awareness as well as adaptive management approaches that allow for flexibility in response to changing conditions. This includes addressing arsenic contamination in regions where it has previously not been a concern due to shifting groundwater patterns or land use practices.

Advancements in water quality monitoring, remote sensors, real-time data collection, and advanced data analytics and IoT will enable more efficient and proactive monitoring of arsenic levels. Policies and protocols implemented should focus on groundwater management and land use practices to prevent arsenic from entering drinking water sources. Regulations could play a crucial role in addressing As contamination, with governments and regulatory bodies continuously reviewing and applying stringent controls and actions.

Global collaborative R&D initiatives are needed to solve this global problem, and so it is important for all of the leading organisations, including WHO, UN, and UNESCO, to proactively engage in collaborative efforts on global platforms. Such platforms should facilitate discussions on knowledge and experiences related to arsenic and its impact, innovative solutions and technologies, and policies that can effectively combat arsenic contamination globally. A concrete example of successful collaboration is the Joint FAO/WHO Expert Committee on Food Additives (JECFA), which assesses the safety of food additives, contaminants, and veterinary drugs [20]. Expanding such collaborative initiatives to explicitly address arsenic contamination can enhance global awareness and prompt corrective action. Therefore, by fostering interdisciplinary collaboration, international organisations can contribute to a holistic understanding of arsenic contamination and its far-reaching consequences.

5. Conclusions

Arsenic contamination poses a substantial and far-reaching threat with profound implications for both global environmental sustainability and public health. This discussion has underscored the following key aspects: (i) the environmental and public health impact of arsenic footprints, (ii) the critical role of awareness and education, and (iii) mitigation approaches encompassing detection methods and removal strategies. These insights collectively contribute to a comprehensive framework aimed at controlling and preventing arsenic contamination in water sources. However, the journey towards a sustainable solution demands continued research, development, and innovation. Our ultimate objective is to ensure that communities worldwide have unfettered access to safe and arsenic-free water, safeguarding both human health and the environment. This aspiration necessitates a concerted effort on multiple fronts, encompassing public awareness and education as well as governmental, legislative, and regulatory measures. The global challenge of arsenic contamination calls for collaborative networks that bring together academia, development agencies, and local communities across all countries, irrespective of varying levels of development. Through collective action, we can forge a path towards a healthier future, where access to safe water is recognised as a fundamental right for all. This collaborative endeavour is essential for preserving the well-being of humanity and our planet, exemplifying the transformative impact that is achievable when united in the pursuit of a common goal.

The emerging analytical techniques, including portable sensors and advanced IoT technologies and databases, will provide sensitive and rapid information about arsenic detection. This will help in obtaining information on arsenic contamination quickly, which will further help in taking the appropriate actions via collaborative international efforts and regulatory measures.

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