

A Mini Review on Arsenic Contamination in Drinking Water: Emerging Trends, Advanced Remediation Technologies, and Public Health Implications

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Author Details

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Abstract

Arsenic pollution in drinking water remains a major global health concern, particularly in regions with naturally arsenic-rich geological formations. This review examines the sources, emerging trends, and advanced remediation solutions for arsenic in drinking water, along with the associated public health concerns. Natural geological processes are the primary source of arsenic in groundwater, but human activities, such as industrial contamination, exacerbate the issue. Climate change, increased groundwater extraction, and weak regulatory frameworks also contribute to evolving pollution patterns. Advanced remediation technologies such as novel adsorbents, electrochemical methods, and bioremediation have shown promise in enhancing arsenic removal efficiency. Nevertheless, issues such as high operational costs, maintenance challenges, and waste generation remain significant. Prolonged exposure to arsenic through drinking water can lead to various health problems, including cancer, cardiovascular disease, and developmental disorders. Vulnerable populations—such as children and low income communities are especially at risk. This analysis highlights the need for long-term, cost-effective water treatment technologies, stronger regulatory measures, and public health initiatives to mitigate the negative impacts of arsenic contamination worldwide.

Keywords: Arsenic contamination, Drinking water, Remediation technologies, Public health impact, Groundwater pollution

Introduction

Arsenic pollution in drinking water is a major global health concern with far-reaching consequences. Arsenic, a naturally occurring element, can enter water sources through geological processes such as the leaching of arsenic-containing rocks into groundwater [1]. However, human activities including industrial pollution and improper waste management have significantly worsened contamination levels in many regions. It is estimated that over 200 million people worldwide are exposed to arsenic concentrations exceeding the World Health Organization (WHO) recommended limit of 10 µg/L, putting them at risk for serious health effects [2].

Arsenic pollution in drinking water varies significantly by geography, ranging from very low levels in some regions to extremely high concentrations in others (Table 1). Studies conducted in California, USA, have found arsenic concentrations in groundwater ranging from 2µg/L to 15µg/L, which have been associated with skin lesions and respiratory issues [3]. In Bangladesh, one of the most severely affected

countries, arsenic concentrations in drinking water have been reported to reach as high as 120 µg/L, significantly increasing the risk of skin cancer and developmental abnormalities [4]. In West Bengal, India, groundwater arsenic concentrations range from 10µg/L to 50µg/L, which can lead to lung cancer and cardiovascular problems [5].

Arsenic levels in surface water in Xinjiang, China, range from 20 to 200µg/L, which can lead to hypertension and bladder cancer [6]. Arsenic has a significant negative impact on human health; long-term exposure is associated with various illnesses, including neurological disorders, cardiovascular disease, developmental abnormalities, and several types of cancer (such as skin, lung, and bladder cancer). Vulnerable populations—including children, the elderly, and residents of low-income communities are more likely to experience these health effects due to higher water intake, weakened immune systems, and limited access to healthcare resources [7]. Efforts to reduce the impacts of arsenic contamination have led to the development and implementation of various remediation approaches.

Table 1: Summary of the minimum to maximum arsenic concentrations, water sample types, locations, health impacts, remediation techniques, and references discussed.

Min. As Concentration ($\mu\text{g/L}$)	Max. As Concentration ($\mu\text{g/L}$)	Water Sample Type	Location	Health Impact	Remediation Techniques	Reference
2	15	Groundwater	California, USA	Skin lesions, respiratory issues	Activated alumina, reverse osmosis	[3]
5	120	Drinking water	Bangladesh	Skin cancer, developmental defects	Iron-based filtration, ion exchange	[4]
10	50	Groundwater	West Bengal, India	Lung cancer, cardiovascular disease	Activated carbon, bio-remediation	[5]
20	200	Surface water	Xinjiang, China	Bladder cancer, hypertension	Reverse osmosis, electrocoagulation	[6]
10	75	Groundwater	Punjab, Pakistan	Neurological disorders, low birth weight	Hybrid treatment systems, electrochemical	[7]
5	35	Drinking water	Argentina	Developmental delays, gastrointestinal issues	Biochar, graphene oxide adsorption	[8]
13	293	Groundwater	Punjab, Pakistan	Hepatitis, Stomach pain, Bladder, gastrointestinal issues	Filtration, Sedimentation	[16]

These include activated alumina, reverse osmosis, and ion exchange, which have been used to remove arsenic in regions such as Bangladesh and California [3]. In West Bengal, activated carbon and bioremediation techniques have been employed to lower arsenic levels [4]. Electrocoagulation and hybrid treatment methods have proven effective in high-concentration areas, such as Xinjiang, China [6, 8].

The purpose of this paper is to provide a comprehensive examination of the causes and patterns of arsenic contamination in drinking water, emerging treatment technologies, and potential public health consequences. It will also address the challenges of reducing the risks associated with arsenic exposure, particularly in low-resource settings.

Sources and Trends of Arsenic Contamination

The majority of arsenic contamination in drinking water is caused by natural geological processes. Arsenic is released into groundwater in certain areas due to the presence of arsenic-rich rocks in the Earth's crust. Regions with volcanic, sedimentary, or metalliferous deposits are more likely to exhibit elevated arsenic levels. In these areas, groundwater often a primary source of drinking water can become contaminated through leaching processes, during which arsenic gradually enters the water over time [2,7]. Arsenic pollution is caused by both human activities and natural processes. Industrial operations such as mining, the use of arsenic-based insecticides, and the improper disposal of arsenic-containing waste can all contaminate drinking water sources.

Emissions from coal combustion and nonferrous metal smelting further exacerbate the issue. In many developing countries, rapid industrialization combined with weak regulatory frameworks contributes to widespread contamination of drinking water sources [2,9]. Recent investigations have revealed an alarming rise in arsenic contamination

levels in areas previously considered safe. Climate change-induced fluctuations in groundwater levels and shifts in precipitation patterns both of which can influence the mobilization of arsenic into water supplies are key factors driving this trend. Additionally, the increased reliance on groundwater in arid regions, due to diminished surface water availability, has led to deeper groundwater extraction, which often results in higher arsenic concentrations [1,10].

Advanced Remediation Technologies

Previously, arsenic was removed from drinking water using standard filtration processes such as activated alumina, iron-based adsorbents, and reverse osmosis. These methods were widely adopted due to their simplicity, efficiency, and low cost. While they can effectively remove arsenic, they often have drawbacks, such as high operational costs, the need for frequent maintenance, and the generation of toxic waste by-products. In recent years, there has been significant interest in developing novel adsorbents for arsenic removal. Biochar, graphene oxide, and modified clay have shown considerable promise due to their large surface area and adsorption capabilities. Biochar, made from organic waste, is particularly appealing because of its low cost, renewable nature, and environmental benefits. Due to its enormous surface area, graphene oxide has demonstrated great effectiveness in arsenic removal, making it an ideal choice for low-cost water treatment systems in impoverished countries [11].

Electrochemical approaches, such as electrocoagulation and electrochemical oxidation, have recently gained popularity as advanced arsenic removal methods. These techniques use electrical currents to promote the precipitation of arsenic compounds or to break down arsenic species into less toxic forms. Membrane methods, including nanofiltration and reverse osmosis, have also been shown to effectively reduce arsenic levels. Despite their high removal efficiency, these

systems often suffer from fouling, high energy consumption, and high maintenance costs [12].

A developing technique for removing arsenic is bioremediation, which uses microorganisms to break down or immobilize pollutants. Some bacteria and fungi can either adsorb arsenic onto their cellular surfaces, reducing its bioavailability, or transform it into less harmful forms (such as converting arsenate to arsenite). Although it is still in the experimental phase, bioremediation offers a viable and environmentally sustainable solution to groundwater arsenic contamination [13]. Hybrid and integrated treatment systems, which combine several technologies to enhance arsenic removal, have also been a focus of recent advancements in arsenic remediation. For example, the overall effectiveness and sustainability of arsenic removal can be improved by combining biological treatment with adsorption methods or electrochemical techniques. These hybrid systems often provide greater flexibility, lower costs, and a reduced environmental impact [14].

Public Health Implications

Chronic arsenic exposure through drinking water has been linked to a variety of health issues, primarily due to its carcinogenic properties. Long-term arsenic exposure is associated with an increased risk of skin, lung, bladder, and liver cancers. Arsenic has also been shown to affect the cardiovascular system, causing hypertension and other cardiovascular problems. The harmful effects of arsenic extend to developmental processes, with prenatal exposure linked to birth defects, low birth weight, and neurodevelopmental issues [15,16]. Certain groups are more vulnerable to the health impacts of arsenic exposure, including children, the elderly, and individuals with pre-existing conditions. Children are particularly at risk due to their higher water intake relative to body weight and their developing organs, which are more vulnerable to toxic insults. Additionally, individuals living in poverty-stricken areas with limited access to clean water are disproportionately affected, as they often rely on contaminated water sources for drinking and cooking [17, 18].

Social and Economic Impacts

Arsenic exposure has far-reaching public health consequences. Widespread arsenic contamination can have a significant impact on healthcare systems, especially in low-income countries with limited resources. Increased healthcare costs, reduced productivity, and the need for expensive remediation measures can strain already vulnerable economies. Furthermore, the social stigma associated with arsenic exposure can lead to isolation, discrimination, and mental health issues. Governments and international organizations play a crucial role in addressing the arsenic pollution issue. The WHO and other health agencies recommend a maximum arsenic concentration of 10µg/L in drinking water. However, many countries, particularly those with limited resources, have struggled to implement and enforce these standards. To mitigate the risks of arsenic exposure, stronger regulatory frameworks, increased monitoring, and enhanced public awareness efforts are needed.

Challenges and Future Directions

Although significant progress has been made in detecting and treating arsenic-contaminated drinking water, several challenges remain. One of the most significant barriers is the lack of affordable and sustainable treatment technologies in many underdeveloped countries. Additionally, dealing with diverse water sources, varying arsenic concentrations, and local environmental factors complicates the development of universally applicable solutions. Future research should focus on developing more cost-effective, scalable, and energy-efficient treatment methods, as well as improving public health education and policy interventions.

Conclusion

Arsenic pollution in drinking water is a major global health con-

cern with widespread consequences for both individuals and societies. As our understanding of arsenic sources and health effects advances, so too must the technologies and regulations designed to mitigate its impact. Emerging advancements in remediation technologies, such as novel adsorbents, electrochemical treatments, and hybrid systems, hold promise for more efficient and sustainable solutions. However, addressing the issue of arsenic contamination requires a collaborative effort among governments, researchers, and communities to ensure safe drinking water for all. With continuous research and investment, it is possible to reduce the harmful effects of arsenic and protect public health in vulnerable regions worldwide.

Conflict of Interest

The authors declare there is no conflict of interest.

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