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REVIEW

Sources and Control Strategies of Arsenic in the Atmosphere

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ABSTRACT

Arsenic (As), classified as a Group I carcinogen by the International Agency for Research on Cancer (IARC), poses severe risks to ecosystems and human health through atmospheric exposure. This review synthesizes current knowledge on the sources, health impacts, and control strategies of atmospheric arsenic, with an emphasis on its global transport and toxicity. Natural sources, such as volcanic eruptions and soil erosion, contribute approximately 2.1 Gg/year; however, anthropogenic activities, notably metal smelting and coal combustion, dominate emissions, with global anthropogenic releases reaching approximately 28.6 Gg/year. Atmospheric arsenic primarily exists in two forms: particulate matter ($PM_{2.5}$-bound As(V)/As(III) and methylated species) and gaseous forms (e.g., AsH_3, As_2O_3), facilitating long-range transport and cross-continental pollution, as evidenced by Asian emissions contributing 39% of Arctic deposition. Advanced techniques, such as inductively coupled plasma mass spectrometry (ICP-MS) and models like GEOS-Chem, enhance emission tracking; however, gaps persist in monitoring gaseous arsenic and refining emission inventories. Health risks include lung cancer, neurotoxicity, and cardiovascular diseases, exacerbated by inhalation and dietary exposure via contaminated crops. Control technologies, including calcium- and iron-based adsorbents and industrial scrubbers, show promise but face challenges related to efficiency and cost. Regional strategies, such as China's tightened emission limits (0.5 mg/m^3) and the EU's Best Available Techniques (BAT), highlight progress, yet global cooperation remains vital for transboundary mitigation. Future research should prioritize low-cost sensors, elucidating speciation-toxicity relationships, and AI-driven emission management to address data gaps and optimize policies. Integrating multidisciplinary approaches—advanced science, stringent regulations, and international collaboration—is crucial to mitigate the environmental and public health impacts of arsenic amid growing industrialization and climate change.

Keywords: Atmospheric Arsenic; Anthropogenic Emissions; Health Risks; Control Technologies; Global Transport

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1. Introduction

Arsenic (As), a metalloid element widely present in nature, poses a significant threat to the ecosystem and human health [1, 2]. The International Agency for Research on Cancer (IARC) has clearly classified it as a Group I carcinogen, demonstrating that even trace amounts of arsenic exposure may lead to serious health problems [3–5]. Globally, arsenic pollution, through various pathways such as water, soil, and the atmosphere, poses long-term environmental risks and threatens public health [6, 7].

In past research, the issues related to arsenic exposure through drinking water have been relatively well explored, with many studies detailing its impact mechanisms on human health and its migration and transformation patterns in the water environment [2, 5, 6]. However, there is still a lack of systematic and comprehensive understanding of the presence forms, migration and transformation laws of arsenic in the atmosphere, as well as the resulting health risks [8, 9]. Arsenic in the atmosphere mainly exists in particulate form (e.g., As(V), As(III), and methylated arsenic species) and gaseous form (e.g., AsH_3 and As_2O_3) [10]. These different forms of arsenic have different physical and chemical properties, and they can be transported over long distances in the atmosphere, thereby affecting areas far from pollution sources and expanding the scope of arsenic pollution [8, 11].

With the acceleration of the global industrialization process, various industrial activities are becoming more frequent, and the anthropogenic emissions of arsenic are showing a continuously increasing trend [12]. Asia and South America play a dominant role in the global arsenic emission pattern having become the primary emission regions [13, 14]. This emission situation not only poses a direct threat to the local ecological environment and the health of residents but also has a profound impact on other regions around the world through atmospheric transport [9, 14, 15].

Atmospheric arsenic originates from both natural and anthropogenic sources, with the latter becoming increasingly dominant due to industrial activities. Natural sources include volcanic eruptions, wildfires, and dust storms, which release arsenic trapped in minerals into the atmosphere. However, anthropogenic emissions, including coal combustion, non-ferrous metal smelting, and pesticide use, account for over 70% of global atmospheric arsenic deposition [12, 13]. Coal-fired power plants are the largest contributors, as arsenic volatilizes during high-temperature combustion and subsequently condenses onto fine particulate matter ($PM_{2.5}$), facilitating long-range transport [8, 11]. In regions such as South Asia and South America, artisanal gold mining and agricultural burning exacerbate emissions, resulting in localized hotspots with severe health implications [14, 15]. Recent studies highlight a worrying trend. Despite regulatory efforts, atmospheric arsenic levels in developing nations continue to rise due to lax enforcement and rapid industrialization [12]. For instance, in Bangladesh and India, coal-based energy production and unregulated smelting operations have resulted in air arsenic concentrations exceeding World Health Organization (WHO) guidelines by 10–20 times [9, 13]. Even in remote areas like the Arctic, atmospheric transport from industrial regions has resulted in detectable arsenic deposition, underscoring its global dispersion [8]. Climate change may further intensify this issue, as increased wildfires and dust storms under warming conditions could amplify natural arsenic emissions [15]. Addressing these challenges requires not only stricter emission controls but also international cooperation to mitigate transboundary pollution.

Unlike waterborne arsenic, which primarily enters the body through ingestion, atmospheric arsenic poses a dual threat via inhalation and dermal absorption, with particulate-bound arsenic species [As(III) and As(V)] being the most hazardous [10, 11]. Once inhaled, these particles penetrate deeply into the lungs, where they undergo biochemical transformations, releasing reactive arsenic species that induce oxidative stress, DNA damage, and epigenetic changes associated with lung cancer, cardiovascular diseases, and neurotoxicity [3, 5]. Methylated arsenic gases (e.g., dimethylarsine) are equally concerning, as they can diffuse directly into the bloodstream through alveolar membranes, bypassing metabolic detoxification pathways [10].

This review aims to integrate the latest research progress and conduct a detailed analysis of the sources, monitoring methods, health effects, and control technologies of atmospheric arsenic. Deeply discussing these key aspects provides a solid theoretical basis for formulating scientific and reasonable global arsenic pollution prevention and control strategies, with the expectation of contributing to improving the global atmospheric environment quality and protecting human health.

2. Sources and Emissions of Arsenic

2.1. Natural Sources

Natural processes contribute significantly to global arsenic emissions, with an estimated annual release of approximately 2.1 Gg of arsenic into the atmosphere [8, 9]. Among these natural sources, volcanic activities dominate, releasing substantial quantities of arsenic-containing gases (e.g., arsine) and particulate matter during eruptions [16, 17]. The median arsenic-to-sulfur (As/S) ratio in volcanic emissions, measured at 1.59×10^{-4} g/g, serves as a critical metric for assessing volcanic contributions to atmospheric arsenic levels [18, 19]. Regions with active volcanism, such as the Altiplano-Puna plateau in South America, often exhibit localized spikes in arsenic concentrations, sometimes increasing by 10 to 100 times during eruptions, posing acute ecological and health risks [11, 16].

Soil wind erosion is another key natural source, particularly in arid and semi-arid regions where sparse vegetation exposes soil to wind forces [3, 9]. Arsenic adsorbed onto fine soil particles becomes airborne, which contributes to atmospheric loading. While global emissions from this process are modest, their impact can be pronounced in areas prone to dust, such as the Sahel or Central Asia. It was found that arsenic-laden dust storms elevate local exposure levels [13, 19–21].

Biological emissions include the microbial methylation of inorganic arsenic into volatile compounds (e.g., methylarsines) [22, 23]. Recent studies highlight the role of marine and terrestrial microbiomes in this process, with methylated arsenic species detected in remote oceanic and wetland atmospheres [10, 22]. For instance, Breuninger et al. [10] identified dimethylarsine as a significant biogenic contributor in coastal regions.

Globally, background arsenic concentrations from natural sources typically remain below 0.1 ng/m³ [11]. However, episodic events like volcanic eruptions or dust storms can disrupt this baseline, underscoring the need for dynamic monitoring. For example, in Patagonia, historic volcanic eruptions dispersed arsenic over vast areas, with legacy effects still detectable in soils and water [15]. Such variability complicates risk assessments, particularly in regions where natural emissions overlap with anthropogenic pollution (e.g., mining areas) [23]. Future research should prioritize quantifying biogenic fluxes and refining models to disentangle natural vs. anthropogenic arsenic pathways, especially under climate change scenarios that may intensify soil erosion and microbial activity [20, 21].

2.2. Anthropogenic Sources

Anthropogenic activities are the main contributors to atmospheric arsenic emissions [24]. The global anthropogenic arsenic emissions are approximately 28.6 Gg per year, far exceeding natural source emissions, which is more than 13 times that of natural sources [9]. Among anthropogenic sources, the metal smelting industry plays a dominant role, especially in the smelting processes of metals (e.g., copper, lead, and zinc) [25, 26]. Taking copper smelting as an example, during the smelting process, the volatilization rate of arsenic can reach 30%, resulting in a large amount of arsenic entering the atmospheric environment [25]. The intricate chemical reactions and high-temperature conditions in metal smelters facilitate the release of arsenic, turning these industrial sites into major pollution hotspots. As one of the largest metal producers in the world, China contributed 15.5 Gg of arsenic emissions from the non-ferrous metal industry in 2005, approximately, fully demonstrating the significant impact of the metal smelting industry on atmospheric arsenic pollution (**Figure 1**) [8, 9]. This data not only reflects China's industrial scale but also serves as a wake-up call for the urgent implementation of more stringent pollution control measures within the metal smelting sector.

Coal-fired power plants are recognized as a significant source of atmospheric arsenic [27, 28]. Coal generally contains a certain amount of arsenic, with a content ranging from 0.5 to 80 mg/g [28]. During the coal combustion process, more than 90% of the arsenic accumulates in fly ash, but a considerable amount is still emitted into the atmosphere with the flue gas [27]. With the continuous growth of global energy demand, coal, one of the primary energy sources, poses an increasingly significant problem of arsenic emissions [29]. The widespread reliance on coal-fired power generation in many developing and developed countries results in a substantial cumulative impact of these emissions on the global atmosphere. Moreover, as energy demands continue to surge, finding cleaner alternatives to coal or developing more efficient arsenic capture technologies for coal-fired plants has become a critical challenge for environmental protection.

In addition to metal smelting and coal-fired power plants, activities such as the use of wood preservatives, the application of arsenic-containing pesticides, and waste incineration also release a certain amount of arsenic [30]. During the use of wood preservatives, arsenic in chromated copper arsenate (CCA) will gradually be released into the atmosphere [31, 32]. CCA is a chemical wood preservative containing chromium, copper, and arsenic [32]. The long-term exposure of treated wood to environmental elements, such as sunlight, rain, and wind, accelerates the release of arsenic, contributing to low-level but persistent atmospheric contamination. Additionally, the application of arsenic-containing pesticides in agricultural production will also cause arsenic to enter the atmospheric environment [3]. This not only affects the air quality in rural areas but can also have cascading effects on the local ecosystem, potentially harming beneficial insects, birds, and other wildlife. During the waste incineration process, the burning of arsenic-containing substances will release the arsenic species into the atmosphere [33]. Incineration plants, if not properly equipped with advanced pollution control devices, can act as significant sources of arsenic emissions, spreading pollutants over wide areas and impacting the health of nearby communities.

Chile in South America has become a hotspot of arsenic pollution in the Southern Hemisphere due to its large-scale copper mining activities [17, 34, 35]. In some areas of Chile, the local atmospheric arsenic concentration reaches as high as 30 ng/m³, significantly impacting local air quality and the health of residents [36–38]. Prolonged exposure to such elevated arsenic levels has been linked to a range of health issues, including respiratory diseases, skin disorders, and an increased risk of certain cancers. In addition, in some agricultural areas of Southeast Asian countries, such as Myanmar and Cambodia, emissions from biomass burning (e.g., crop straw) are significant [39, 40]. During the crop harvest season, a large amount of straw is burned, and the arsenic contained in it is emitted into the atmosphere through combustion, causing pollution to the local atmospheric environment [41]. This traditional agricultural practice, while deeply ingrained in local cultures, exacerbates air quality problems, especially when combined with other sources of pollution. It highlights the need for sustainable agricultural practices that can reduce the reliance on biomass burning and mitigate the associated environmental and health risks. Overall, addressing atmospheric arsenic pollution requires a multi-faceted approach that encompasses technological innovation, policy reforms, and public awareness campaigns to curb the various anthropogenic sources and safeguard the environment and human health.

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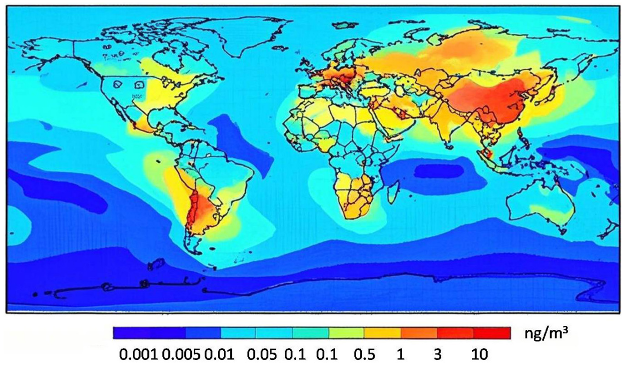

Figure 1. The spatial distribution of atmospheric arsenic concentrations in 2015, as simulated by GEOS-Chem. The map is reproduced from Wai et al. [8] with permission from the American Chemical Society.

3. Forms and Transport of Arsenic in the Atmosphere

3.1. Chemical Speciation

The form distribution of arsenic in the atmosphere is relatively complex. Particulate arsenic accounts for more than 90% of the total amount, which is mainly adsorbed on the surface of fine particles (e.g., $PM_{2.5}$) [9, 20]. This fine particulate association allows arsenic to travel long distances in the atmosphere, facilitating its dispersion across regions and even continents. Studies near copper smelters have detected inorganic arsenic associated with airborne particulates [42]. In these areas, As(V) dominated the PM10 and PM2.5 fractions, accounting for 95–98% and 96–97%, respectively [11, 42]. The dominance of As(V) in particulate matter near industrial sources can be attributed to the high-oxygen environments generated during smelting processes, which promote the oxidation of arsenic. Comparable findings were reported in research conducted at Doñana National Park in Spain [43], suggesting that industrial emissions have a widespread impact on the distribution of arsenic forms in the atmosphere. Additionally, elevated atmospheric arsenic levels have been observed near non-ferrous metal smelters [43], further emphasizing the role of industrial activities in shaping the atmospheric arsenic profile.

Under different environmental conditions, the chemical forms of arsenic vary greatly. In an oxygen-rich environment, pentavalent arsenic [As(V)] is the predominant form, accounting for more than 95% of the particulate arsenic [7, 13, 14]. This stability of As(V) in oxidizing conditions is due to its relatively high oxidation state, which makes it less reactive in the presence of oxygen. In comparison, trivalent arsenic [As(III)] is more stable under reducing conditions [3, 6]. For instance, in the anoxic environments of certain industrial wastewater treatment systems or deep soil layers, As(III) can accumulate and persist. This difference in form will affect the toxicity and environmental behavior of arsenic. Generally, the toxicity of As(III) is stronger than that of As(V) [5, 7]. As(III) can more readily bind to biological molecules, such as enzymes and proteins, thereby interfering with vital cellular processes and causing oxidative stress. In contrast, As(V) is less reactive and often less toxic in biological systems.

Gaseous arsenic is also an important part of atmospheric arsenic, primarily including arsine (AsH_3) and arsenic trioxide (As_2O_3) [12]. As_2O_3 has strong chemical activity and can react with alkaline substances [38]. For example, it reacts with Na_2CO_3 to form sodium arsenite ($NaAsO_2$) [15]. This reactivity allows As_2O_3 to participate in various chemical reactions in the atmosphere, potentially altering its distribution and toxicity. Arsine, on the other hand, is a highly toxic and flammable gas that can pose immediate risks to human health and safety in industrial settings where it may be produced. Although the concentration of organic arsenic in the atmosphere is relatively low compared to inorganic species, common organic arsenic compounds such as monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA) have been detected in aerosols, precipitation, and cloud water, with their presence attributed to biogenic processes like microbial methylation and anthropogenic emissions [10]. Jakob et al. [6] found that methylated arsines exhibit short atmospheric half-lives (1-2h) under UV light at 20°C, with trimethylarsine (TMAs) degrading within hours to form TMAO, DMA, and MMA via photochemical oxidation. Under dark conditions, their half-lives range from 2 days to 19 weeks, decreasing with higher methylation. Mestrot et al. [12] further showed that methylated arsines undergo rapid degradation under UV via hydroxyl radical (·OH) addition, with half-lives of 7–8 hours for $MeAsH_2$, Me_2AsH, and Me_3As. While the oxidation products (MMA, DMA, and TMAO) are stable in atmospheric particulate matter (PM_{10}), their persistence is linked to particle dynamics (e.g., adsorption and wet deposition). TMAO dominates PM_{10} samples (66–69%), indicating its environmental prevalence. Recent findings suggest that these organoarsenicals are widespread as background chemicals, likely due to biovolatilization, with their formation being a global phenomenon. However, their specific degradation pathways in air and long-term environmental fate require further study.

A study from Breuninger et al. [10] detected trace levels (~0.001 ng/m3) of methylated arsenic species [e.g., monomethylarsonic acid (MMAsV), dimethylarsinic acid (DMAsV), and trimethylarsine oxide (TMAsVO)] in precipitation, cloud water, and aerosols collected at the high-altitude Pic du Midi Observatory in France (**Figure 2**). This research reveals the complex sources and transport mechanisms of organic arsenic. TMAsVO exhibited a mixed terrestrial and marine biogenic source, with significant contributions likely coming from coastal regions. DMAsV were primarily derived from marine biogenic activity, showing strong correlations with marine sulfur compounds (e.g., methanesulfonic acid) [10]. The levels of inorganic arsenic (iAs) and MMAsV were linked to terrestrial (especially anthropogenic) sources, such as fossil fuel combustion and industrial emissions [29]. Methylated arsenic species in aerosols were found to be more soluble than inorganic arsenic, making them more prone to wet deposition (e.g., rainfall) and increasing their bioavailability in surface environments [10, 20]. This enhanced bioavailability means that organic arsenic can more easily enter the food chain, potentially posing risks to both wildlife and human health. Laboratory experiments under environmentally relevant conditions (e.g., UV exposure) showed no detectable conversion of inorganic arsenic to methylated species, ruling out abiotic processes as a significant source [10]. Although their concentrations are not high, the toxicity of organic arsenic cannot be ignored [7]. Some studies have shown that organic arsenic may undergo metabolic transformation in the human body, posing a potential health risk [7]. For example, certain enzymes in the human liver can convert less toxic organic arsenic species into more harmful forms, highlighting the need for further research into the metabolic pathways and health impacts of organic arsenic.

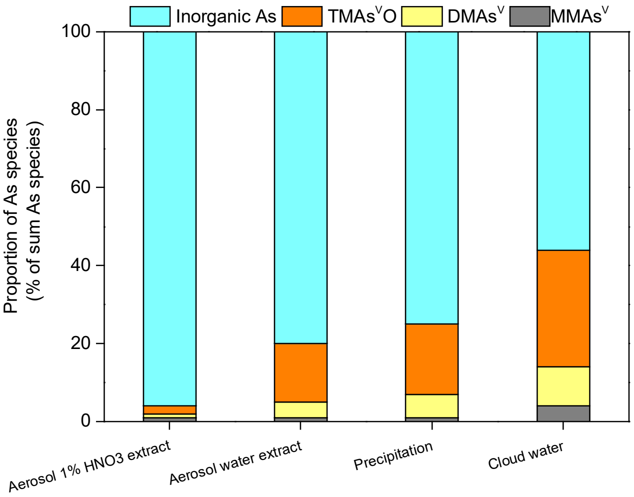

Figure 2. The variability in arsenic (As) species proportions across different atmospheric deposition samples. The stacked bars represent the relative abundances (% of total As species) of monomethylarsonic acid (MMAsV), dimethylarsinic acid (DMAsV), trimethylarsine oxide (TMAsVO), and inorganic As in (1) 1% HNO_3 aerosol extracts, (2) aerosol water extracts, (3) precipitation, and (4) cloud water.

Source: Breuninger et al. [10].

3.2. Transport Mechanisms

Atmospheric arsenic has a relatively long average residence time, generally 4 to 5 days, which allows it to be transported intercontinentally, thereby affecting areas far from pollution sources [8]. Wind-driven dispersion allows these fine particles to travel long distances, with their atmospheric residence time influenced by particle size and local meteorological conditions. Near emission sources, arsenic-containing aerosols typically deposit at an average rate of 0.2 cm/s, though standard deposition rates are closer to 0.1 cm/s [44]. A Netherlands-based study reported dry deposition rates of 0.5% per hour and wet deposition rates of 1.2–1.5% per hour, estimating an atmospheric lifetime of 2.5 days for arsenic aerosols—sufficient for transport over 1,000 km or more [44]. Deposition dynamics are further shaped by industrial factors, including stack height, plume velocity, and proximity to emission sources [44]. Urban areas typically exhibit higher atmospheric arsenic contributions than rural regions. Deposition rates also vary spatially: remote areas average 0.5 µg/m²/day, rural areas <3 µg/m²/day, urban zones 3–9 µg/m²/day, and areas near emission sources >15 µg/m²/day [45].

However, the existing studies on arsenic transport mechanisms have limited information on comprehensively explaining the altitude-dependence of long-range transport. Generally, as altitude increases, the atmospheric density decreases, which may affect the behavior of arsenic-containing particles [44, 45]. For instance, at higher altitudes, the particles may experience less frictional resistance and be more likely to be carried over longer distances by the stronger jet streams. Also, the temperature and pressure changes with altitude can influence the physical and chemical properties of arsenic-containing aerosols, potentially altering their deposition rates. Moreover, the role of boundary layer dynamics in modulating deposition has not been adequately explored [8, 44, 45]. The atmospheric boundary layer, which is the lowest part of the atmosphere directly affected by the Earth's surface, plays a crucial role. Turbulence within the boundary layer can enhance the mixing of arsenic-containing particles, either promoting their deposition through increased interaction with the surface or delaying it by keeping them suspended in the air [8, 44, 45]. Additionally, the height and stability of the boundary layer, which are influenced by factors such as surface heating, wind shear, and the presence of obstacles, can impact the residence time of arsenic in the boundary layer and, consequently, its deposition rate [8, 44, 45]. Understanding these altitude-related and boundary-layer-related factors is essential for a more comprehensive understanding of arsenic transport and deposition processes.

Through model simulations, arsenic emissions in South America play a dominant role in the pollution pattern in the Southern Hemisphere, contributing up to 90% of the arsenic deposition in Antarctica (**Figure 3a**) [8]. Similarly, it has been found that arsenic emissions in Asia can be transported over long distances and affect North America and the Arctic region with the help of the westerlies [8]. Results showed that the contribution of arsenic emissions in Asia to the arsenic deposition in the Arctic region is significant, reaching 39% of the total deposition in the Arctic region (**Figure 3b**) [8].

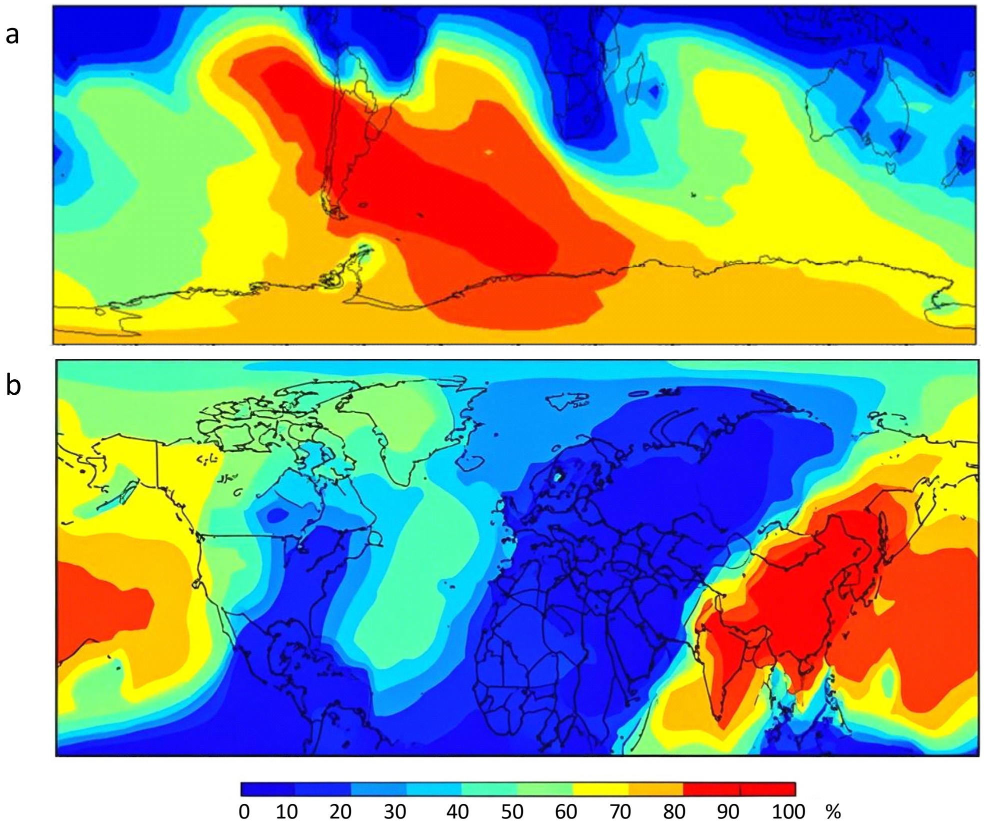

Figure 3. The source attribution of arsenic deposition, depicting the percentage contribution of total atmospheric arsenic emissions from (**a**) South America and (**b**) Asia. The map is reproduced from Wai et al. [8] with permission from the American Chemical Society.

Wet and dry depositions are the main removal pathways of atmospheric arsenic [6, 8]. The wet deposition flux is relatively large, approximately 25.4 Gg per year, while the dry deposition flux is relatively small, approximately 5.3 Gg per year [6, 8]. Observational studies in the Netherlands have found that the average lifespan of arsenic aerosols in the atmosphere is approximately 2.5 days [8, 9]. During this time, they can be transported over a distance of more than 1000 kilometers with the wind [11, 45]. Meteorological conditions such as precipitation intensity and wind speed have a significant impact on the transport distance of arsenic [16]. Strong precipitation can remove arsenic from the atmosphere more quickly through wet deposition, and the magnitude of wind speed directly affects the transport speed and distance of arsenic [20]. Additionally, topographic factors also influence the transport of arsenic [36, 46]. For example, terrains such as mountains may block the transport path of arsenic, resulting in the enrichment of arsenic in local areas [46].

4. Monitoring and Analysis Methods

4.1. Sampling Techniques

In atmospheric arsenic monitoring, the high-volume sampler (with a flow rate of 1.13 m^3/min) combined with filter membrane collection is the widely adopted mainstream method [11, 45]. This method is favored for its ability to collect a large volume of air samples over a relatively short period, enabling the detection of even low-concentration arsenic in the atmosphere. The selection of the filter membrane is crucial for accurately monitoring the atmospheric arsenic content [11]. Different types of filter membranes have different performance characteristics (**Table 1**).

Glass fiber filters have the advantage of low cost, but their blank values are relatively high, generally ranging from 40 to 60 ng/cm^2, which may interfere with the monitoring of trace amounts of arsenic [11]. This high blank value can lead to an overestimation of the actual arsenic content in samples, especially in areas where arsenic concentrations are naturally low or in the early stages of pollution. In contrast, quartz filters have relatively low blank values, usually between 0.5 and 5 ng/cm^2, which makes them more suitable for trace analysis. Their lower blank values ensure more accurate quantification of arsenic, reducing the risk of false positives. Furthermore, Teflon filters exhibit the best performance, with a blank value as low as 0.3 ng/cm^2. However, their relatively high price limits their widespread application to some extent [11]. Despite this limitation, Teflon filters are often used in high-precision research projects where the utmost accuracy is required, such as long-term studies on the impact of arsenic on human health or in areas with extremely low-background arsenic levels.

The "M-type sampler" used in the UK is a sampling device specifically designed for collecting inhalable particles [47, 48]. Its flow rate is set at 0.3 m^3/h, and it can perform continuous monitoring for up to one week [47, 48]. This extended monitoring period enables the capture of temporal variations in arsenic concentration, which is crucial for understanding the dynamic behavior of arsenic in the atmosphere. The design of this sampler facilitates the collection of more representative data on atmospheric arsenic concentrations, particularly for monitoring the arsenic content in inhalable particles [47, 48]. Inhalable particles are of particular concern as they can be directly inhaled into the human respiratory system, posing significant health risks. By focusing on these particles, the "M-type sampler" provides valuable information for assessing the potential exposure of the population to arsenic.

During the sample pretreatment process, acid digestion (such as the HNO_3-H_2O_2 system) is one of the commonly used methods, which can convert arsenic in the sample into an analyzable form [10]. This traditional method has been widely used for its effectiveness in breaking down the matrix of the collected samples. However, in recent years, microwave-assisted extraction technology has gradually been applied [10]. Microwave-assisted extraction utilizes microwave energy to heat the sample in a closed system, accelerating the extraction process. Compared to traditional methods, this technology can increase the recovery rates of elements such as Cr and Ni by 30% and more effectively extract arsenic from the sample, thereby improving the accuracy of monitoring [10]. The enhanced extraction efficiency not only saves time but also ensures that more arsenic is recovered from the sample, leading to more reliable results. Moreover, the controlled environment of microwave-assisted extraction reduces the risk of contamination during the pretreatment process, further enhancing the quality of the analytical data. These advancements in sampling and pretreatment techniques are continuously improving the accuracy and reliability of atmospheric arsenic monitoring, providing more accurate data for environmental research and policy-making to address the issue of arsenic pollution.

Table 1. The summary of the performance characteristics of glass fiber, quartz, and Teflon filters in atmospheric arsenic monitoring [10, 11, 45, 47, 48].

Filter Type	Collection Efficiency	Retention of Semi-Volatile Arsenic	Blank Correction Methods	Key Advantages	Disadvantages
Glass Fiber	High (>99.99% for ≥0.3 μm particles)	Moderate retention; prone to adsorption/desorption due to surface chemistry	High blank values (40–60 ng/cm^2) require frequent blank subtraction and rigorous pre-cleaning	Low cost, high particle capture efficiency	High blank interference for trace analysis
Quartz	Excellent (>99.7% for ≥0.3 μm particles)	Strong retention due to chemical stability and high surface area; suitable for semi-volatile organic compounds	Low blank values (0.5–5 ng/cm^2) allow simple blank subtraction	Low background, thermal stability	Higher cost than glass fiber
Teflon (PTFE)	Exceptional (>99.7% for ≥0.3 μm particles)	Superior retention due to hydrophobicity and chemical inertness; minimizes arsenic volatilization	Ultra-low blank values (0.3 ng/cm^2) enable minimal correction; pre-screening for background	Highest accuracy, chemical resistance. use	High cost, limited widespread

4.2. Analysis Techniques

Table 2 compares the characteristics of the arsenic detection methods in the particulate matter [49, 50]. Atomic absorption spectrometry (AAS) is a commonly used technique for arsenic analysis [50, 51]. It processes samples through a hydrogen-argon flame and can achieve quantitative determination of arsenic, with a detection limit reaching the ng level [50, 51]. This technique has the advantages of relatively simple operation and high accuracy, and has been widely applied in atmospheric arsenic monitoring. The simplicity of AAS makes it accessible for many laboratories, especially those with limited resources or less-experienced technicians. Its high accuracy ensures reliable results for routine monitoring tasks, such as assessing the overall arsenic concentration in urban or industrial areas. For example, in long-term studies tracking the impact of nearby industrial emissions on local air quality, AAS can be used to regularly analyze particulate matter samples to determine if arsenic levels are within acceptable limits or showing signs of increase.

Inductively coupled plasma mass spectrometry (ICP-MS) combined with high-performance liquid chromatography (HPLC) technology can achieve speciation analysis of arsenic [50, 51]. Through this combined technology, different forms of arsenic such as As(III), As(V), and organic arsenic can be accurately distinguished, providing a powerful means for in-depth understanding of the environmental behavior and toxicity of arsenic [50, 51]. Since different arsenic species exhibit varying degrees of toxicity and environmental fate, accurately identifying and quantifying them is essential. For instance, As(III) is generally more toxic than As(V), and understanding their relative proportions in atmospheric particulate matter can help researchers predict potential health risks to humans and ecosystems more accurately. This combined method is often used in research projects aimed at uncovering the sources and transformation mechanisms of arsenic in the environment.

X-ray fluorescence spectrometry (XRF) technology offers the advantage of not requiring sample digestion, allowing for the rapid analysis of arsenic in samples [49, 50]. This non-destructive and rapid analysis feature makes XRF suitable for on-site screening or preliminary analysis. In situations where immediate results are needed, such as during environmental emergency response operations or large - scale sampling campaigns, XRF can be used to quickly identify areas with potentially high arsenic concentrations. However, its detection limit is relatively high, generally 100 ng/cm^2, which limits its monitoring ability for samples with low arsenic concentrations to some extent [49, 50]. As a result, XRF may fail to detect trace amounts of arsenic, and confirmatory tests using more sensitive methods are often required.

Single-particle ICP-MS technology can analyze the physical carrier characteristics of arsenic, helping researchers understand the distribution of arsenic in particles [49, 50]. This is particularly important because the physical properties of the particles carrying arsenic, such as size, shape, and composition, can influence how arsenic is transported in the atmosphere, deposited on surfaces, and interacts with biological systems. For example, understanding whether arsenic is mainly associated with fine or coarse particles can provide insights into the potential inhalation risks for humans. By analyzing the physical carrier characteristics, researchers can also trace the sources of arsenic-containing particles, whether they are from industrial emissions, soil dust, or other origins. This information is invaluable for developing targeted strategies to reduce arsenic pollution and protect public health. Overall, the diversity of these arsenic detection methods allows for a comprehensive approach to studying atmospheric arsenic, from basic quantification to in-depth speciation and source-tracking analysis.

Table 2. Characteristics of the arsenic detection methods in the particulate matter [49, 50].

Analysis Technique	Key Features	Advantages	Limitations
Atomic Absorption Spectrometry (AAS)	Uses hydrogen-argon flame; Quantitative determination Detection limit at ng level	Simple operation; High accuracy	Limited speciation capability
ICP-MS with HPLC	Speciation analysis; Distinguishes As(III), As(V), organic As	High sensitivity; Precise species differentiation	Requires complex instrumentation; Higher cost
X-ray Fluorescence Spectrometry (XRF)	No sample digestion required Rapid analysis	Non-destructive; Fast results	High detection limit (~100 ng/cm²); Less sensitive for low-concentration samples
Single Particle ICP-MS	Analyzes physical carrier characteristics; Particle distribution studies	Provides particle-specific data; High resolution	Requires specialized setup

4.3. Model Simulations

Models including GEOS-Chem and the HYSPLIT backward trajectory model play an important role in the study of atmospheric arsenic [8, 9]. These models can simulate the transport process of atmospheric arsenic by integrating emission inventories and meteorological data. For instance, they have successfully reproduced the cross-border transport of arsenic pollution generated by biomass burning in Asia, providing a powerful tool for studying the transport laws of arsenic pollution between regions [8, 9]. In Wai et al. [8], model results show good agreement with observed surface air As concentrations worldwide, with a high correlation coefficient ($R^2 = 0.98$) and a mean normalized bias of 89%. However, significant overestimations occur in remote areas, such as Alaska and Hawaii, likely due to uncertainties in natural emissions and deposition parameters. Zhang et al. [9] improve the emission inventory and conduct more comprehensive validation. For Europe and the U.S., the mean fractional bias (MFB) ranges from -12% to 62%, and the mean fractional error (MFE) from 26% to 70%, meeting U.S. EPA criteria for $PM_{2.5}$ modeling. For example, in 2005, Europe showed an MFB of -12% and MFE of 26%, while the U.S. had an MFB of 62% and MFE of 70%. The model captures spatial variations well, with high concentrations in Chile and eastern China, though underestimations in some regions and overestimations in others (e.g., India due to coal combustion increased) highlight uncertainties in emission rates and regional transport processes. Overall, the model effectively reproduces As distribution but requires refinement for complex source regions and natural processes. The HYSPLIT backward trajectory model combined with MODIS fire point data can be used to trace the sources of atmospheric arsenic pollution [8, 9]. Through this model, researchers can determine the source directions and transport paths of atmospheric arsenic in different regions. For example, the contribution of Chilean emissions to the enrichment of arsenic in Antarctic snow has been verified through this model, providing an important basis for an in-depth understanding of the global arsenic cycle (**Figure 3a**) [8, 9].

However, current models still have some uncertainties. Emission inventory errors are a significant problem. Especially in developing countries, due to the lack of monitoring data and the complexity of emission sources, the accuracy of emission inventories needs to be improved [8, 9]. Additionally, the limitations of deposition parameterization schemes also impact the simulation accuracy of the models [8, 9]. How to more accurately describe processes such as wet and dry deposition is an important direction for future model improvement.

4.4. The Convergence of Remote Sensing, AI, and Smart Sensor Technologies

The integration of remote sensing (RS), artificial intelligence (AI), and advanced sensor technologies presents transformative opportunities for monitoring arsenic (As) contamination in water and topsoil [52]. These techniques offer scalable, cost-effective, and non-destructive solutions. For example, NASA's Hyperion satellite has demonstrated the ability to correlate soil hyperspectral data with As concentrations using random forest regression ($R^2 = 0.840$), while studies using the EO-1 Hyperion sensor highlighted the value of spectral preprocessing (e.g., second derivative transformation) and dimensionality reduction (e.g., genetic algorithms) to improve model accuracy [53]. Moving forward, combining RS with gravity recovery and climate experiment (GRACE) satellite data on groundwater fluctuations, as proposed in the literature, can enhance the understanding of As mobilization in aquifers [52]. Additionally, the development of high-resolution, multi-temporal RS datasets (e.g., from Sentinel-2 and Landsat 9) will enable more precise mapping of As hotspots, particularly in regions with complex land cover like shrublands, where binary classification models (e.g., multi-layer perceptron with accuracy = 0.693) have shown promise in identifying high-risk zones. In the realm of AI-driven self-learning sensors, neural network-based models such as the fully connected neural network (FCNN) with five hidden layers ($R^2 = 0.692$ on the testing set) demonstrate the potential for real-time recalibration. These models can automatically adjust to environmental variables (e.g., soil moisture and vegetation cover) that influence spectral signatures, reducing measurement errors caused by atmospheric interference or soil heterogeneity [52, 54].

Low-cost, intelligent portable sensors integrated with AI systems represent another frontier. Current lab-based spectrometers and portable digital sensors (e.g., photoresistor-based devices for As detection) provide a foundation, but miniaturizing these technologies with edge AI capabilities (e.g., deploying lightweight ML models on microcontrollers) will enable field-deployable solutions [52, 54]. For example, combining visible near-infrared (VNIR) sensors with AI algorithms (e.g., gradient-boosted regression trees) could allow real-time quantification of particulate As species by analyzing soil or water spectra against pre-trained databases. Such systems, when connected to cloud-based AI platforms, could facilitate crowd-sourced monitoring networks, where citizen scientists use smartphone-linked sensors to contribute data for regional As risk mapping [52, 54]. This approach aligns with studies showing that RS-derived indices (e.g., the normalized difference vegetation index) can serve as proxies for As contamination, especially when integrated with ground-truth data via crowdsourcing.

To our knowledge, no studies have yet reported the use of the above technology to monitor particulate arsenic concentrations. The convergence of RS, self-learning AI models, and low-cost sensor technologies is expected to revolutionize particulate arsenic monitoring, enabling proactive, democratized, and sustainable management of this global contaminant.

5. Health Impacts and Air Quality Standards

5.1. Health Risks

Long-term exposure to an atmospheric environment containing arsenic can cause various hazards to human health, and the increased risk of lung cancer is particularly significant [7]. Studies have shown that the incidence of lung cancer in people near arsenic pollution sources such as smelters is 3 to 5 times higher than that in the normal population [7]. The neurotoxicity of arsenic cannot be ignored either [5]. There is a certain correlation between arsenic and cognitive dysfunction, and long-term exposure may lead to problems such as memory decline and inattentiveness [14]. Skin lesions are typical symptoms of arsenic exposure, and common manifestations include pigmentation and keratosis [33]. These skin problems not only affect the appearance of patients but also may have a serious impact on their quality of life [7]. It is worth noting that there is a synergistic effect between smoking and arsenic exposure. Smokers who drink high-arsenic groundwater (>200 μg/L) have a more than 2-fold increased risk of bladder cancer [7]. This indicates that the superposition of multiple arsenic exposure pathways will further aggravate the harm to human health.

Atmospheric arsenic can also enter the food chain through deposition, posing a potential threat to human health [39]. Studies have found that 80% of the arsenic on the leaves of vegetables near factories originates from atmospheric dry deposition, indicating that people may ingest arsenic from the atmosphere when consuming these vegetables, thereby increasing their health risk [39].

5.2. Air Quality Standards

Currently, there is no unified global standard for arsenic air quality [11]. The European Union has set an annual average concentration limit of 6 ng/m³, aiming to protect public health and reduce the risks associated with arsenic exposure [55]. However, continents such as Asia, North, and South America currently lack specific air quality standards for arsenic, which to some extent reflects the differences in the degree of attention and management strategies for arsenic pollution in different countries and regions [11].

WHO recommends a unit risk value of $1.5\times10^{-3}/(\mu g\cdot m^{-3})$, which means that lifelong exposure to an arsenic concentration of 1 ng/m³ will result in 1.5 new cases of lung cancer per million people [9, 56]. Through actual exposure assessments, it has been found that urban residents in Europe and the United States inhale approximately 40 to 90 ng of arsenic per day, while in rural areas, due to relatively better air quality, the daily intake of arsenic by residents is reduced to less than 50 ng [9, 56].

Given the current situation, it is urgent to establish a global unified standard based on health risks. In particular, for sensitive areas such as schools and workplaces, stricter standards should be formulated to ensure the health and safety of the population.

6. Control Technologies of Arsenic in the Atmosphere

6.1. Adsorbent Technologies for Combustion Emission

Calcium-based adsorbents (e.g., CaO) have potential applications in arsenic removal. In the temperature range of 300–600 °C, CaO can react with As_2O_3 to form $Ca_3(AsO_4)_2$, thereby achieving the capture of arsenic [57]. However, when the temperature exceeds 900 °C, the reaction product $Ca_2As_2O_7$ becomes unstable, resulting in a decrease in the adsorption efficiency of the adsorbent [57].

Iron oxides (Fe_2O_3) have the best adsorption effect on arsenic at 600 °C [58]. However, in practical applications, the presence of SO_2 will affect their adsorption efficiency. SO_2 will compete with arsenic for adsorption sites, thereby reducing the adsorption capacity of iron oxides for arsenic [58].

Activated carbon has a high specific surface area (500–1000 m²/g), providing a large number of adsorption sites and has a good adsorption effect on both gaseous and solid-phase arsenic [59]. Through surface modification, such as loading metals like Pd, the adsorption performance of activated carbon can be further improved [59].

Fly ash adsorption utilizes the adsorption effect of unburned carbon and metal components in fly ash on arsenic [60]. At 120°C, the capture efficiency of fly ash for arsenic can reach 85% [57]. This adsorption method has the advantages of low cost and resource utilization, providing a feasible approach for arsenic pollution control [11].

6.2. After Treatment Techniques of Industrial Applications

In coal-fired power plants, the technology of combining electrostatic precipitation (ESP) with calcium agent injection is usually used to remove particulate arsenic [27]. This method can remove more than 70% of particulate arsenic. However, for gaseous arsenic, the effect of this method is relatively poor [27]. Wet scrubbing systems have a good removal effect on gaseous arsenic; however, during the application process, a large amount of wastewater is generated, which requires subsequent treatment, thereby increasing the treatment cost and environmental risks [27].

The wet scrubbing systems present potential issues regarding secondary pollution, especially in terms of wastewater arsenic speciation [27]. Arsenic in wastewater exists in various valence states, such as As(III) and As(V), and each form has different chemical properties and environmental behaviors. For example, As(III) is generally more toxic and mobile in the environment compared to As(V). The presence of different arsenic species in the wastewater can complicate the subsequent treatment processes. If not properly treated, the release of wastewater containing specific arsenic species may lead to further environmental contamination, such as soil and groundwater pollution. The complex speciation of arsenic in wet scrubbing wastewater requires an in-depth study to develop more effective treatment strategies that can not only remove arsenic but also transform it into less harmful and more stable forms, thus minimizing the overall environmental impact of the wet scrubbing process [61].

Advanced removal methods, including biofiltration, electrochemical techniques, and catalytic oxidation, could remove As contamination in water [61–63]. Biofiltration utilizes hyperaccumulator plants (e.g., *Typha latifolia*) to absorb arsenic from water, achieving up to 89% removal. This low-cost, eco-friendly method avoids harsh chemicals but is slower and sensitive to environmental conditions like pH and temperature. Costs include plant installation, maintenance, and biomass disposal (200–250 US dollars per 1000 kg). Its effectiveness declines with high arsenic concentrations. Biofiltration is economical but requires a slow process [61]. Electrochemical techniques oxidize toxic As(III) to less harmful As(V) using electric currents, enabling efficient removal via precipitation or adsorption. These methods are fast, controllable, and suitable for industrial use, but require high energy input and expensive electrodes. By-products like chlorine gas may also pose environmental hazards, necessitating additional treatment. In addition, electrochemical techniques are efficient but energy-intensive [62]. Catalytic oxidation accelerates As(III) oxidation using catalysts (e.g., metal oxides or enzymes), offering high efficiency even at low temperatures. It is cost-effective and simple, but faces catalyst deactivation from contaminants. Performance may drop with extremely high arsenic levels [63].

Copper smelters in Chile adopt a combination process of baghouse dust removal and sulfide precipitation, which effectively reduces arsenic emissions by 60% [27]. This successful case provides a reference for other similar enterprises, demonstrating the advantages of the combined process in arsenic pollution control. Emerging nano-iron oxide-coated filter materials have shown good arsenic removal performance under laboratory conditions, with a removal rate of AsH_3 exceeding 95% [58]. Although this technology is still in the research stage, it provides new directions and possibilities for future arsenic pollution control.

6.3. Regional Control Strategies

In Asian countries, due to frequent metal smelting and coal combustion activities, the problem of arsenic emissions is relatively prominent [26]. Therefore, the emissions from these two industries need to be prioritized for control. China has revised the emission standards for the non-ferrous metal industry, tightening the arsenic limit to 0.5 mg/m³ [64]. This measure helps to reduce arsenic emissions from the non-ferrous metal industry and improve the atmospheric environmental quality.

In South America, the management of mining waste should be strengthened to reduce the release of arsenic [14, 16]. Chile has legislated to require smelters to install online monitoring systems to monitor arsenic emissions in real-time and take timely measures to control pollution [14, 64].

The European Union promotes the Best Available Techniques (BAT), emphasizing the application of these techniques from the production process [64]. By optimizing the process and equipment, the generation and emission of arsenic can be reduced, rather than simply relying on end-of-pipe treatment [61]. This concept of process control provides a more effective strategy for controlling arsenic pollution.

International cooperation also plays an important role in the treatment of arsenic pollution [65, 66]. For example, the Arctic Council's pollutant action plan can address cross-border arsenic pollution through the joint efforts of various countries, thereby protecting the ecological environment and the health of residents in the Arctic region [65, 66].

7. Challenges and Future Prospects

Currently, the research on atmospheric arsenic faces many challenges. In terms of monitoring, due to the remote geographical location and high monitoring costs in remote areas, there is a severe lack of relevant monitoring data, which makes our understanding of the overall situation of global arsenic pollution incomplete [9]. The analysis technology for gaseous arsenic remains immature, and existing analysis methods have certain limitations in terms of accuracy and sensitivity, making it challenging to meet the monitoring requirements for low-concentration gaseous arsenic. In addition, due to limited monitoring capabilities and complex industrial activities in developing countries, the emission inventories are not entirely accurate, which presents difficulties in accurately assessing arsenic emissions and formulating effective control strategies.

In response to these challenges, future research can be carried out in the following directions: Firstly, develop low-cost and highly sensitive sensors, such as portable devices based on the nano-gold colorimetric method. This device can quickly detect the concentration of atmospheric arsenic on-site, improving the convenience and coverage of monitoring. Secondly, deepen the research on the correlation between the form of arsenic and its toxicity, and establish standard limits for different forms of arsenic, thereby more accurately assessing the health risks of arsenic and formulating more scientific pollution control strategies. Finally, apply artificial intelligence technology to optimize emission prediction and control strategies. By analyzing a large amount of monitoring data and emission data, the accuracy of prediction can be improved, providing more powerful support for policy formulation.

8. Conclusion

This review synthesizes current knowledge on the sources, transport mechanisms, health impacts, and control strategies of atmospheric arsenic, highlighting critical gaps and future directions for research and policy. Anthropogenic activities, particularly metal smelting and coal combustion, dominate arsenic emissions (~28.6 Gg/year), far exceeding natural sources (~2.1 Gg/year). Regions like Asia and South America are hotspots due to intensive industrial and mining activities. Atmospheric arsenic primarily exists as $PM_{2.5}$-bound As(V)/As(III), organic arsenic, as well as gaseous species (e.g., AsH_3 and As_2O_3), with long-range transport enabling cross-continental pollution, as evidenced by Asian emissions contributing 39% of Arctic deposition. Advanced analytical techniques (e.g., ICP-MS and XRF) and models (e.g., GEOS-Chem) have improved tracking, but challenges persist, including gaps in emission inventories and limitations in gaseous arsenic analysis.

Global air quality standards remain inconsistent, with only the EU setting a binding limit (6 ng/m^3). Urgent action is needed to harmonize standards based on health risk assessments, particularly for vulnerable populations. Control technologies, such as calcium/iron-based adsorbents and industrial scrubbers, show promise but face efficiency and cost barriers. Regional strategies, such as the EU's BAT guidelines and China's tightened emission limits (0.5 mg/m^3), demonstrate progress; however, global cooperation is essential to address transboundary pollution.

Future efforts should prioritize: (1) developing low-cost sensors for widespread monitoring, (2) elucidating speciation-toxicity relationships to refine risk assessments, and (3) integrating artificial intelligence for dynamic emission management. In conclusion, mitigating atmospheric arsenic pollution necessitates a multidisciplinary approach that combines advanced science, robust policy, and international collaboration. Addressing data gaps, optimizing control technologies, and enforcing stringent regulations will be pivotal in safeguarding environmental and public health in the face of growing industrialization and climate change.

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