

Arsenic Removal from Groundwater in Small Rural Communities by Electrocoagulation: A Review

Emilija Mohora^{1*}

¹McLean High School, McLean, VA, USA

*Corresponding Author: mohoraemilija@gmail.com

Advisor: Srđan Rončević, srdjan.roncevic@dh.uns.ac.rs

Received December 10, 2025; Revised May 29, 2026; Accepted August 3, 2026

Abstract

Many low-income rural communities worldwide face disproportionate exposure to arsenic-contaminated drinking water. This is largely because many tested remediation technologies remain unaffordable and complex to operate in the rural remote communities. Arsenic originates naturally and from anthropogenic sources in groundwater as carcinogenic, causing health problems to more than 200 million people worldwide. Electrocoagulation (EC) is considered a promising groundwater treatment technology for rural communities due to its proven high-level arsenic removal efficiency (>95%), simple operation and maintenance (O&M), low arsenic-laden sludge production compared with conventional technologies. Nevertheless, EC also has drawbacks and limitations such as electrode passivation, management of arsenic-laden sludge and specific electricity requirements. This review summarizes EC technology, results of several extended field trails and presents advantages, as well as challenges of its applications in rural communities. Future research should prioritize real-time automation of EC systems to enable long term operation with the required removal efficiency, reduce O&M labor costs in high-wage rural markets and develop cost-effective, local strategies for stabilizing and reusing arsenic-laden sludge.

Keywords: Drinking water, Arsenic removal, Electrocoagulation, Operational cost, Rural communities

1. Introduction

The lack of access to safe drinking water is one of most significant challenges facing our planet. One out of every four individuals do not have access to safe drinking water in their homes (UNICEF, 2021). Globally, 884 million people lack safe drinking water and over 2.6 billion lack basic sanitation. Each year, water- and sanitation-related diseases cause about 1.5 million deaths in children under five and lead to 443 million lost school days. Thus, on July 28, 2010, the United Nations (UN) recognized access to safe, clean water as a human right (UN, 2010).

More than half of the world's population depends on groundwater resources for drinking water (WHO, 2022),. Factors such as surface water pollution, population growth, and climate change have contributed to increased reliance on groundwater. Geogenic arsenic present in groundwater reserves poses a substantial risk, as approximately 200 million people across at least 70 countries have been exposed to drinking water with arsenic concentrations exceeding the WHO guideline value of 10 µg/L. Arsenic in groundwater is a critical issue in at least 30 low and lower middle-income countries with a daily incomes of US\$ <3.00 and US\$ 4.20, respectively (World Bank, 2025). In conterminous U.S., about 41 million people which is about 14% of the total population use a domestic well for household use (Maupin et al., 2010). Among them, 2.1 million people use water with arsenic concentration higher than USEPA guideline value of 10 µg/L and is thus a national health concern (Ayotte et al., 2017).

Arsenic exists in groundwater in two forms, arsenic (III) and arsenic (V). Studies have shown that the toxicity of arsenic (III) is several times greater than arsenic (V). Arsenic is identified by the WHO as one of ten chemicals posing significant public health concerns. It is identified as a Group I human carcinogen (IARC, 2016) with slope factor of

1.5 per mg/kg-day (USEPA, 2016). Initial indications of prolonged exposure to elevated concentrations of inorganic arsenic, commonly via drinking water or food, typically manifest in dermatological symptoms such as pigmentation alterations, skin lesions, and hyperkeratosis of the palms and soles. Hence, long-term exposure to arsenic leads to chronic health problems such as hyperpigmentation and keratosis of the hands and feet; it also causes bladder, lung, skin, kidney, liver, and prostate cancer (Smith et al., 2006, Zheng et al., 2015).

Various treatment technologies are known to be efficient in arsenic removal from groundwater below the WHO guideline value, including coagulation/filtration, modified coagulation filtration, adsorption on activated alumina, reverse osmosis, oxidation/filtration ion exchange, adsorption by adsorbents such as granular ferric oxides, iron oxide coated sand (USEPA, 2000, Höll et al., 2010). However, from the rural setting perspective (fewer than 10,000 residents) these treatment technologies take considerable time, require an extensive set-up and skilled operators to oversee the treatment processes, the entire treatments require several pH adjustments as well as the addition of acid, coagulants, mainly iron or aluminium salts, generate a considerable quantity of secondary pollutants and large volume of arsenic-laden sludge, posing serious environmental problems if not managed properly (Nidheesh and Annantha Singh, 2017).

US Environmental Protection agency (EPA) conducted an Arsenic Demonstration Program to assess arsenic removal efficiency, long-term performance, capital expenditure (CAPEX), and operation and maintenance (O&M) costs for 50 small water treatment systems between 2003 and 2011. The program examined technologies adsorptive media (AM), iron removal (IR), coagulation/filtration (C/F), ion exchange (IX), reverse osmosis, and point-of-use devices (USEPA, 2011). The O&M cost ranged from \$0.02 to \$6.05/m³ of treated groundwater. AM had a lower capital, but a higher O&M cost than IR, C/F, and IX. The media replacement cost for the AM systems averaged 80% of the O&M cost and was the main cause of the higher O&M cost of the AM systems (USEPA, 2011, Sorg et al., 2015). The program found that many approved treatment solutions require high CAPEX, extensive O&M by trained technicians, and safe disposal of arsenic-laden sludge, making them unaffordable for small rural communities. For that reason, an alternative treatment method is needed for rural communities, and EC has emerged as a promising simple technology for community-scale groundwater treatment, gaining global research interest in the last twenty years.

A literature review indicates that a considerable number of review articles published between 2015 and 2026 have examined the application of EC for arsenic removal from groundwater, primarily focusing on laboratory-scale EC system design and operational parameter optimization. Nevertheless, only few reviews have reported the results of extended EC field trials (Kobya et al., 2020), and to the best of the authors' knowledge, no reviews have systemically summarized the advantages and disadvantages of EC use for arsenic removal from groundwater in small rural and remote communities in both developing and developed countries. Therefore, there is a need for review focus on results of the recent extended EC systems field trails for arsenic removal from groundwater and its advantages and drawbacks for small rural communities.

A literature search was carried out using the Scopus, ResearchGate, Google Scholar databases for studies published between 2010 and 2026. The literature search focused on electrocoagulation and its use for removing arsenic from groundwater, along with keywords related to extended field tests, rural communities. After screening the titles, abstracts, and full texts, only peer-reviewed studies published in English that examined community-scale EC use were included. Studies focused solely on theory, laboratory settings, wastewater or irrelevant to application of EC in small rural drinking water systems were excluded.

2. EC Fundamentals

Electrocoagulation (EC) is an electrochemical water-treatment process in which coagulant metal ions are generated “*in situ*” by applying electrical energy to sacrificial electrodes. These ions destabilize colloidal suspensions, leading to flocculation, where small arsenic-containing particles and coagulant hydroxides combine into larger masses called flocs, which are then removed through flotation or sedimentation (Fig. 1). When a direct current (DC) is

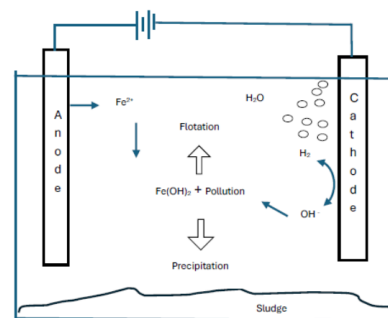


Figure 1. Principal reactions and interactions in an EC system.

applied, the metal anode undergoes electrochemical oxidation, releasing metal ions (e.g., Al^{3+} or Fe^{2+}) into the water. In EC systems using iron electrodes, both monomeric species and polymeric hydroxyl metal complexes are produced, with their composition strongly influenced by water pH (Koby et al., 2020).

Anodic reactions (Fe anodes): At the anode, iron is oxidized in a two-step process depending on the applied potential, producing ferrous and ferric ions:



In parallel, oxidation of water also occurs when current is introduced in the process of electro-dissolution:



Cathodic reactions (Fe cathodes): At the cathode, hydrogen gas evolves according to:



The Fe^{3+} ions released at the anode undergo progressive hydrolysis, forming $Fe(OH)_3(s)$ in the absence of competing species. Arsenic is removed primarily through coprecipitation or adsorption, in which arsenic species substitute hydroxyl groups in iron hydroxides (Koby et al., 2020). The destabilized colloids aggregate into larger clusters (flocs), and hydrogen bubbles generated at the cathode attach to these flocs, lifting them to the surface via electro-flotation. Heavier flocs may settle by gravity, enabling solid-liquid separation.

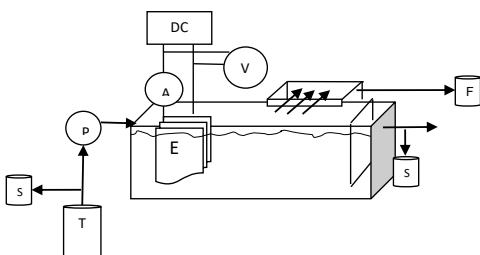


Fig 2. Exsample of an horizontal flow continous EC reactor (T – feed tank, P- centrifugal pump, E- Fe plate electrodes, O – overflow for evacuation of flocks, F – flock, DC power source)

The effectiveness of EC in removing arsenic from groundwater depends on the several factors such as EC systems physical design and operation mode (batch where a fixed volume of groundwater is treated in EC reactor without inflow or outflow or continuous mode when groundwater flows constantly through EC reactor (Fig 2.), electrode materials (Al, Fe, hybrid Fe-Al), electrode arrangements and interelectrode distance, current density, charge loading rate, initial water pH, groundwater chemistry and initial arsenic concentration.

Standardized performance metrics and data normalization are necessary for consistent cross-study comparisons, given the differences in experimental operational conditions, EC

system types, electrode materials and its shapes.

The calculation of the EC system arsenic removal efficiency ($R_{As}(\%)$) is defined as (Koby et al., 2020)

$$R_{As}(\%) = \frac{(C_0 - C_{t_{EC}}) \times 100}{C_0} \quad (5)$$

where C_0 is concentration of arsenic in raw groundwater and $C_{t_{EC}}$ residual As concentration after EC treatment. Charge loading is defined as the charges transferred in electrochemical reactions for a given amount of water treated and is calculated using Eq (6):

$$q_{As,WHO} \left(\frac{C}{L} \right) = \frac{I \times t_{EC,WHO}}{v} \quad (6)$$

where $q_{As,WHO}$ is charge loading $\left(\frac{C}{L} \right)$, i is applied current (A), $t_{EC,WHO}$ is minimum EC time required to achieve WHO guideline value in respect to residual As concentration (s) and v is volume of groundwater in the EC reactor (L).

The EC system operational cost (OC) can be preliminary estimated using Eq. (7):

$$OC = aC_{electricity,reactor} + C_{arsenic-laden\ sludge} + aC_{electricity,pump} + labor\ cost \quad (7)$$

where $C_{elec,exp}$ as explained above is specific actual electrode consumption in $kg\ Fe/m^3$, $C_{electricity,reactor}$ (kWh/m^3) is specific electrical energy consumed by the EC reactor per m^3 of treated groundwater and $C_{arsenic-laden\ sludge}$ is cost of adequate management (transport, treatment and disposal) of arsenic-laden sludge. $C_{electricity,pump}$ is electrical energy consumed by EC reactor pump per m^3 of treated groundwater (in the case of continual mode of operation). Laboratory-scale EC systems with Fe, Al as well as hybrid Fe-Al electrodes have demonstrated consistent high level

of arsenic removal to concentration below WHO/US EPA guideline value for residual arsenic in treated groundwater (Kobya et al., 2020).

3. Results of extended EC systems field trials

Amrose and coworkers (Amrose et al., 2013) successfully operated a 100 L batch EC reactor prototype with 10 mild-steel plate electrodes connected to a sedimentation tank for coagulant addition (Aluminum Sulfate) and solid/solution separation in Amirabad Village in West Bengal, India. For Charge loading ($q_{As,WHO}$) of 350 C/L groundwater with initial arsenic concentrations (C_0) in the range of 343 – 245 $\mu\text{g/L}$ was successfully remediated well below WHO guidance value. The OC cost including electricity and iron electrodes consumption was estimated at \$0.22/ m^3 of treated water, which was \$5.56/annually at the family level, assuming 10 L consumption per person daily. OC did not include cost of labor, EC reactor maintenance and arsenic-laden sludge management. The same team of researchers in 2014, performed 3.5 months long trail to remediate 65 m^3 groundwater with initial arsenic concentration (C_0) of 266 $\mu\text{g/L}$ by testing scale up 600 L Electro Chemical Arsenic Remediation (ECAR) prototype reactor with 10 mild-steel plate electrodes in Dhophdhopi High School in West Bengal, India. They demonstrated ECAR's ability to constantly reduce arsenic concentration in treated water below 5 $\mu\text{g/L}$ for operational charge loading ($q_{As,WHO}$) of 400 C/L (Fig 3.). The OC cost including electricity and iron electrodes consumption was estimated at \$0.83 – \$1.04/ m^3 (Amrose et al., 2014).

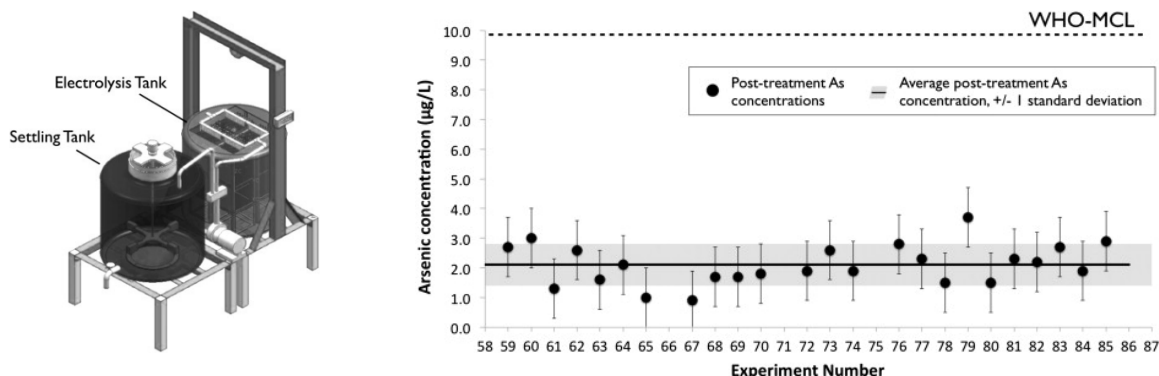


Fig 3. ECAR system and total arsenic concentration in treated groundwater during trail at Dhophdhopi High School in West Bengal was well below WHO guideline value. Reprinted from Amrose et al. (2014) with permission from Elsevier.

For the treatment of groundwater from Temerin and Zrenjanin in Serbia, Orescanin and the team (Orescanin et al., 2013) developed a 1000 L/day pilot-scale EC system. EC system had two phases of treatment starting with Fe EC followed by Al EC and ozonization simultaneously. In the final phase EC treated water was pumped in sedimentation reservoir. Arsenic removal efficiency ($R_{As}(\%)$) was nearly 100%.

Neelanjan and his team performed two extended field trials of continuous EC systems with iron electrodes in the Kaya High school in rural Kaya community and Kayadanga community in West Bengal, India. The EC system in Kaya High school, with install treatment capacity of 100 kL/day was providing 1.25 L/day for 800 students. The EC system was treating groundwater with arsenic initial concentrations (C_0) fluctuating in the range 60 to 110 $\mu\text{g/L}$. The Kayadanga EC system had a significantly higher install capacity of 1,500 kL/day, providing 20 L/day for 800 inhabitants. The initial arsenic concentrations (C_0) in groundwater fluctuated between 60 and 80 $\mu\text{g/L}$. Both EC systems achieved an arsenic removal efficiency of 90%, when supplemented with activated alumina for final polishing resulting in treated water with arsenic concentrations below the WHO guideline value. The OC cost including electricity, labor, replacement of iron plate electrodes was estimated at US\$0.076/ m^3 for Kaya High school to US\$0.091/ m^3 for Kayadanga community. For comparison the OC cost of treating groundwater in the same rural settlements by activated alumina was US \$ 0.293/ m^3 (Neelanjan et al., 2021). The same team of researchers performed extended two months field trail of a hybrid system composed of EC reactor, sand filter and activated alumina unit in rural settlement Lakshmipur in West Bengal. The arsenic natural concentration (C_0) in groundwater was 110 $\mu\text{g/L}$. The estimated drinking water demand was 7800 L/day for the community and local primary school. EC systems

achieved a continuous arsenic removal efficiency of 97 %, when supplemented with activated alumina resulting in treated water with arsenic concentrations below the WHO guideline value. The OC cost including electricity and iron electrodes consumption was estimated at \$0.22/ at US\$0.93/m³ (Neelanjan and Anirban, 2022).

Table 1: Results of extended EC systems field trials

Country	C _{As,0} [µg/L]	Reactor type and volume [L]	Electrode material	Charge dose [C/L]	R _{As} [%]	OC [\$/m ³]	Ref.
W. Bengal India	90 - 760	B, 100	Mild Steel	350	>97	0.22	Amrose et al. (2013)
W. Bengal India	266	ECAR, 600	Mild Steel	450	>98	0.83-1.04	Amrose et al. (2014)
Serbia	75 – 88	100	Fe, Al		100		Orescanin et al. (2013)
W. Bengal India	60 – 110	C	Fe	12	90	0.076 – 0.091	Neelanjan et al. (2021)
W. Bengal India	110	C	Fe	60	97.5	0.93	Neelanjan and Anirban (2022)
USA	250	ACAIE, 1000	Steel	300	>95	0.02 - 0.09	Bandaru et al. (2025)

B- Batch, C – Continuous, ECAR - Electro Chemical Arsenic Remediation, ACAIE- air cathode assisted iron electrocoagulation.

Bandaru et al. (2025) tested a pilot-scale air cathode assisted iron electrocoagulation (ACAIE) system with a 600 L/h capacity in Allensworth, California, where average groundwater arsenic concentration was (C_0) 252 µg/L. They demonstrated ACEIE's ability to constantly reduce arsenic concentration in treated water below USA EPA guideline value for EC system operational charge loading ($q_{As,WHO}$) of 300 C/L during testing between May and November 2022 (Fig 4.). The OC cost including electricity, replacement of iron electrodes was estimated at \$0.02/L and when labor cost of full-time operator is included OC costs, was \$0.09/L.

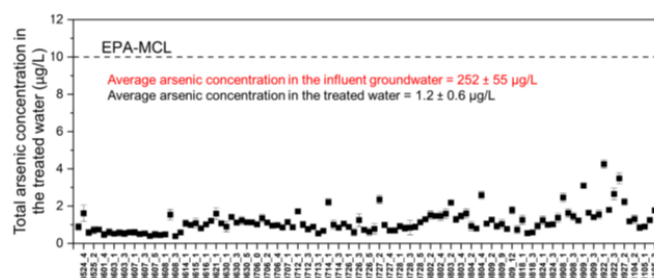


Fig 4. Total arsenic concentration in the ACAIE treated groundwater from rural settlement Allensworth in California from May to November 2022 (Bandaru et al., 2025).

4. EC advantages and drawbacks

Despite the complexity of operational factors that drive EC system arsenic removal efficiency such as reactor geometry, electrode material, applied current, pH, laboratory-scale and extended pilot -scale research confirmed its high level arsenic removal efficiency from groundwater (>95%) (Amrose et al., 2013, 2014, Kobya et al., 2020, Neelanjan et al., 2021, Bandaru et al., 2025).

The main EC operational costs present specific electricity consumption and the replacement of the sacrificial electrodes (Bandaru et al., 2025). In rural and remote areas without access to grid electricity, EC systems can run on batteries that are recharged using renewable sources like solar or wind power. Chamteut et al. (2019) used EC system with installed treatment capacity of 0.5 m³ per day and specific energy consumption of 2.33 kWh/m³ and they confirmed that the EC system fully operability using 750 W solar panels along with batteries, without the need for external energy sources.

During EC processes utilizing direct current electricity, an impermeable oxide film progressively forms on the cathode. This occurrence, known as cathode passivation, presents a significant challenge for prolonged EC system operation that causes a reduction in ionic transfer between electrodes and reducing the EC system arsenic removal efficiency. Various methods of preventing and controlling electrode passivation have been applied such as changing electrode polarity, mechanical cleaning of electrodes (Amrose et al., 2013, 2014) and introducing inhibiting agents (Bandaru et al., 2025). The most efficient and reliable method was periodic mechanical deep cleaning of electrodes

with electrode polarity change. However, in US business environment, electrode mechanical cleanup related labor cost increased OC cost of ACAIE operation from \$0.02 to \$0.09 per L of treated groundwater (Bandaru et al., 2025).

The EC systems also generate arsenic-laden sludge, and if not properly managed, has the potential to release contaminants into soil and groundwater, resulting in secondary contamination. EC process generates approximately 50 mg of arsenic-laden sludge per L of treated groundwater (Abhisek et al., 2019). Hence, EC sludge must be managed strictly in compliance with national regulations and standards. At a minimum, two tests Total Threshold Limit Concentration (TTL) and Soluble Threshold Limit Concentration (STLC) are required to determine the classification of EC system generated sludge waste (e.g., hazardous or non-hazardous) and guide appropriate waste management practices. The cost of EC sludge management is estimated at 5% of groundwater OC cost (Amrose et al., 2013).

5. Conclusion

The review summarizes the suitability of EC technology for the removal of arsenic from groundwater for rural communities. Review of the recent extended EC field trials confirmed highly efficient arsenic removal performance (> 95 %) of EC systems under real conditions. During extended field trials, several months of operation, EC systems in different regions and groundwater chemistry constantly achieved below WHO/USEPA guidance value of arsenic in treated groundwater. The EC systems operated reliably, and the preliminary estimated OC was \$0.83 – \$1.04/m³ in India and \$90/m³ (inclusive of labor cost) in the United States. Additional research is needed to optimize real-time EC system monitoring and process automatization which could control electrode passivation and lower required O&M technician hours, labor cost, and make EC more affordable for small rural communities, particularly in developed markets where labor cost is high compared with developing countries. Additional studies should prioritize developing efficient, locally tailored, and cost-effective approaches for stabilizing and reusing arsenic-laden hazardous sludges, aiming to lower its high waste management costs.

References

- Amrose, S.E., et al. (2013). Arsenic Removal from Groundwater Using Iron Electrocoagulation: Effect of Charge Dosage Rate. *J Environ Sci Health A Tox Hazard Subst Environ Eng.*, 48(9), 1019-1030. <https://doi.org/10.1080/10934529.2013.773215>
- Amrose, S. E. et al. (2014). Electro-chemical arsenic remediation: Field trials in West Bengal, *Science of the Total Environment* 488 – 489, 539 – 546. <https://doi.org/10.1016/j.scitotenv.2013.11.074>
- Bandaru, S. R. S., et al. (2025). Field testing of an affordable zero-liquid-discharge arsenic-removal technology for small-community drinking water systems in rural California. *Water*, 17(3), 374. <https://doi.org/10.3390/w17030374>
- Chamteut, O. et al. (2019). Field demonstration of solar-powered electrocoagulation water treatment system for purifying groundwater contaminated by both total coliforms and arsenic. *Environmental Technology*, 42(3), 397–409. <https://doi.org/10.1080/09593330.2019.1629634>
- Dutta, N., & Gupta, A. (2022). Development of arsenic removal unit with electrocoagulation and activated alumina sorption: Field trial at rural West Bengal, India. *Journal of Water Process Engineering*, 49, 103013. <https://doi.org/10.1016/j.jwpe.2022.103013>
- Dutta, N., Halder, A., & Gupta, A. (2021). Electrocoagulation for arsenic removal: Field trials in rural West Bengal. *Archives of Environmental Contamination and Toxicology*, 80(1), 248-258. <https://doi.org/10.1007/s00244-020-00799-8>.
- Kobya, M., et al. (2020). A review on decontamination of arsenic-contaminated water by electrocoagulation: Reactor configurations and operating cost along with removal mechanisms. *Environmental Technology & Innovation*, 17, 100519. <https://doi.org/10.1016/j.eti.2019.100519>

Maupin, M. A., et al. (2014). *Estimated use of water in the United States in 2010* (U.S. Geological Survey Circular 1405, p. 64). U.S. Geological Survey. <https://pubs.er.usgs.gov/publication/cir1405>

Nidheesh, P. V., & Singh, T. S. A. (2017). Arsenic removal by electrocoagulation process: Recent trends and removal mechanism. *Chemosphere*, 181, 418–432. <https://doi.org/10.1016/j.chemosphere.2017.04.082>

Oreščanin, V., et al. (2013). Preparation of drinking water used in water supply systems of the towns Zrenjanin and Temerin by electrochemical methods. *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering*, 48(13), 437-445. <https://doi.org/10.1080/10934529.2013.729896>

Roy, A., et al. (2019). Concrete stabilization of arsenic-bearing iron sludge generated from an electrochemical arsenic remediation plant. *Journal of Environmental Management*, 233, 141-150. <https://www.sciencedirect.com/science/article/pii/S0301479718313276>

Smith, A. H., et al. (2006). Increased mortality from lung cancer and bronchiectasis in young adults after exposure to arsenic in utero and in early childhood. *Environmental Health Perspectives*, 114(9), 1293–1296. doi: 10.1289/ehp.8832

Sorg, T. J., et al. (2015). The costs of small drinking water systems removing arsenic from groundwater. *Journal of Water Supply: Research and Technology—AQUA*, 64(2), 219–234. <https://doi.org/10.2166/aqua.2014.044>

UNICEF. (2021, June 30). Billions of people will lack access to safe water, sanitation and hygiene in 2030 unless progress quadruples – warn WHO, UNICEF. *UNICEF*. Retrieved November 22, 2025, from <https://www.unicef.org/press-releases/billions-people-will-lack-access-safe-water-sanitation-and-hygiene-2030-unless>

United Nations (2010). The human right to safe drinking water was first recognized by the UN General Assembly and the Human Rights Council. United Nations. <https://docs.un.org/en/A/RES/64/292>

United States Environmental Protection Agency. (2011). *Cost of arsenic removal technologies for small water systems: Arsenic removal technology demonstration program, 2011*. U.S. Environmental Protection Agency. Retrieved November 25, 2025. <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100CAXP.PDF?Dockey=P100CAXP.PDF>

World Bank. (2025). *Poverty & inequality platform*. World Bank. Retrieved December 5, 2025, <https://pip.worldbank.org/home>

World Health Organization (WHO), UNICEF, and the World Bank. (2022). *State of the world's drinking water*. Geneva, Switzerland: World Health Organization; New York, NY: UNICEF; Washington, DC: World Bank. ISBN 9789280652901

Zheng, Y., & Ayotte, J. D. (2015). At the crossroads: Hazard assessment and reduction of health risks from arsenic in private well waters of the northeastern United States and Atlantic Canada. *Science of the Total Environment*, 505, 1237–1247. <https://doi.org/10.1016/j.scitotenv.2014.10.089>