SASTA OLIPHANT

SCIENCE AWARDS

Prize Winner

Science Writing

Year 11 - 12

Jack Yingjian Li

Pembroke School - Middle School

Alkali extraction and reductive precipitation as a novel pathway for arsenic recovery from wastewater sludge

Oliphant Science Awards Entry · Science as a Human Endeavour Task

Introduction

Groundwater arsenic contamination is a significant global health challenge, affecting over 55% of countries (Sultan et al., 2025). As a toxic carcinogen, arsenic exposure causes skin lesions, cancer and developmental issues (World Health Organisation, 2022). Previous arsenic removal methods reduce water toxicity but yield arsenic-laden waste sludge disposed of in landfill, where arsenic can leach back into and recontaminate waterways (Souza and Ciminelli, 2023). Scientific understanding has been applied to create a novel treatment that recycles arsenic from waste sludge, preventing waterway recontamination and supporting sustainable development, while simultaneously presenting an unexpected phosphorus co-recovery benefit (Wang and van Genuchten, 2025). Government policies around critical minerals including arsenic have reduced financial burden on companies adopting this novel method, influencing uptake.

Chemical Background

For decades, arsenic has been removed from groundwater through adsorption onto iron oxyhydroxide, improving drinking water quality (grey in Figure 1). However, during waste disposal into landfill, arsenic is concentrated into sludge and can leach into waterways. The new recovery treatment (blue in Figure 1) removes arsenic from sludge, preventing waterway recontamination. Overall, arsenic treatment encompasses two phases – existing procedures and novel procedures.

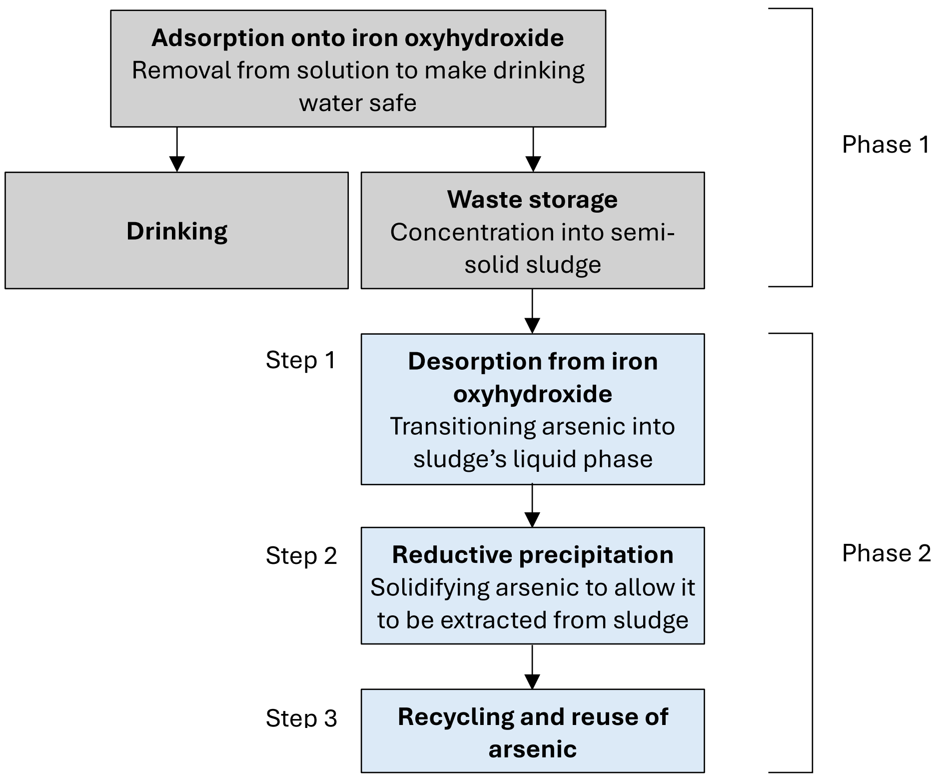

Figure 1. *Flow chart depicting existing arsenic treatment (phase 1) in grey, and the novel arsenic recovery method (phase 2) in blue, which combine to illustrate the full arsenic treatment process.*

Phase 1 – existing procedures to reduce water toxicity
In phase 1, iron oxyhydroxide is added to groundwater. Arsenic adsorbs onto it, removing arsenic from groundwater.

Iron oxyhydroxide is a solid crystal lattice made of Fe^{3+} centres bridged by oxygen-containing groups (Guo et al., 2023). Each inner Fe^{3+}atom bonds to six oxygen atoms octahedrally (see Figure 2) through coordinate bonds: covalent bonds where both shared electrons come from one of the bonding atoms (Das, 2017).

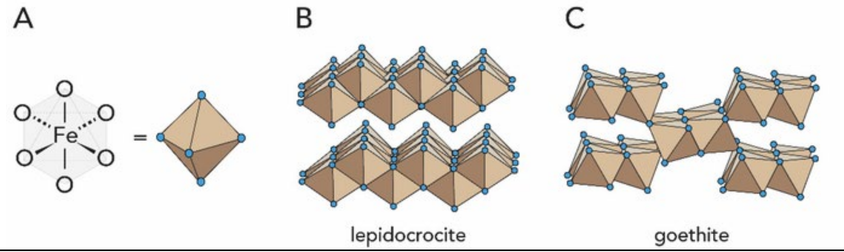

Figure 2. *The octahedral structure around iron atoms in two types of iron oxyhydroxides: lepidocrocite and goethite (Moura and Unterlass, 2020).*

On the solid's surface, some iron atoms are under-coordinated (not fully surrounded by oxygen atoms as they would be within the lattice). To establish stable coordination environments, these iron atoms bind hydroxyl groups, forming $\mathrm{Fe-OH}$ surface complexes. These hydroxyl groups act as ligands: molecules or ions that donate a lone electron pair to a metal ion to form a coordinate bond (University of Texas, 2021). Arsenic-containing species can also act as ligands. Since the $\mathrm{Fe-O-As}$ configuration is more stable than $\mathrm{Fe-OH}$, arsenic ligands can displace some hydroxyl ligands to be adsorbed onto iron oxyhydroxide (Wang et al., 2022). Resultantly, the surface contains a mixture of $\mathrm{Fe-OH}$ and $\mathrm{Fe-O-As}$ sites. Adsorbing arsenic to the solid surface removes it from groundwater, reducing drinking water's toxicity (Chi et al., 2024).

Wastewater containing arsenic and iron oxyhydroxide particles is then concentrated into semi-solid sludge for waste disposal. However, arsenic species in sludge may unwantedly leach into and recontaminate waterways. Phase 2 addresses this issue.

Phase 2 (novel arsenic-recovering procedures)
Phase 2 prevents waterway arsenic recontamination by collecting arsenic from sludge, achieved by adding required chemicals to desorb arsenic species into sludge's liquid phase and then reductively precipitating them out of liquid phase as elemental arsenic.

Step 1: Desorbing arsenic from iron oxyhydroxide into sludge's liquid phase
$\mathrm{Fe-OH_{(s)}}$ and $\mathrm{Fe-O^-_{(s)}}$ exist in equilibrium on iron oxyhydroxide's surface in sludge (Satpathy et al., 2021, Wang and van Genuchten, 2025, Wang et al., 2022):

$$\underset{\text{acid}}{\mathrm{Fe-OH_{(s)}}} + \underset{\text{base}}{\mathrm{OH^-_{(aq)}}} \rightleftharpoons \underset{\text{conjugate base}}{\mathrm{Fe-O^-_{(s)}}} + \underset{\text{conjugate acid}}{\mathrm{H_2O_{(l)}}}. \quad (1)$$

Alkaline $\mathrm{NaOH_{(aq)}}$ is added to sludge's liquid phase, which dissociates into $\mathrm{Na^+}$ and $\mathrm{OH^-}$. Resultantly, sludge's pH is close to 14 and higher than the system's acid strength of $\mathrm{p}K_a = 10.9$ (Satpathy et al., 2021), calculated using the following equation (Gilbert-Kawai and Wittenberg, 2014):

$$\mathrm{pH} = \mathrm{p}K_a + \log\left(\frac{[\text{conjugate base}]}{[\text{acid}]}\right).$$

When $\mathrm{pH} > \mathrm{p}K_a$ as in reaction 1, the deprotonated form (conjugate base) $\mathrm{Fe-O^-_{(s)}}$ is favoured (University of Texas, 2013). This creates reactive $\mathrm{-O^-_{(s)}}$ groups that bond with neighbouring iron atoms, creating larger crystalline iron oxyhydroxide structures. As the lattice grows, the surface area to volume ratio reduces, decreasing available sorption sites. This destabilises surface $\mathrm{Fe-O-As}$ coordination complexes, desorbing arsenic species and moving them into sludge's liquid phase (Wang and van Genuchten, 2025). Electrostatic repulsion between negatively charged $-O^-_{(s)}$ and arsenic species further strengthens desorption.

Arsenic, now in sludge's liquid phase, is primarily present in two substances which exist in equilibrium (Mondal et al., 2013):

$$\underset{\text{hydrogenarsenate}}{HAsO_4^{2-}{}_{(aq)}} + OH^-_{(aq)} \rightleftharpoons \underset{\text{arsenate}}{AsO_4^{3-}{}_{(aq)}} + H_2O_{(l)} \tag{2}$$

Due to the addition of alkaline NaOH, $[OH^-]$ increases, upsetting the system at equilibrium. By Le Chatelier's principle, the system attempts to counteract the change in $[OH^-]$ by decreasing $[OH^-]$, thus favouring the forward reaction and shifting equilibrium right. Arsenic thus predominantly exists as arsenate. Since arsenate's charge density is higher than hydrogenarsenate's, arsenate experiences stronger electrostatic repulsion with iron oxyhydroxide's surface $-O^-_{(s)}$ groups, preventing re-adsorption.

Step 2: Reductive arsenic precipitation

After desorbing arsenate into sludge's liquid phase, step 2 converts this arsenate to solid arsenic by adding thiourea dioxide (TDO): $(NH_2)_2CSO_2$ (Wang and van Genuchten, 2025).

The elevated pH destabilises TDO and cleaves the C-S bond, yielding non-toxic urea $(NH_2)_2CO$ and the strong reducing agent SO_2^{2-} (Zhu et al., 2023):

$$TDO_{(aq)} + 2OH^-_{(aq)} \rightarrow urea_{(aq)} + SO_2^{2-}{}_{(aq)} + H_2O_{(l)} \tag{3}$$

Then, the sulphur atom loses 4 electrons, transitioning its oxidation state from +2 to +6 and oxidising SO_2^{2-}:

$$SO_2^{2-}{}_{(aq)} + 4OH^-_{(aq)} \rightarrow SO_4^{2-}{}_{(aq)} + 2H_2O_{(l)} + 4e^- \tag{4}$$

Arsenic gains 5 electrons to decrease its oxidation state from +5 to 0, reducing arsenate:

$$AsO_4^{3-}{}_{(aq)} + 4H_2O_{(l)} + 5e^- \rightarrow As_{(s)} + 8OH^-_{(aq)} \tag{5}$$

Overall,

$$5SO_2^{2-}{}_{(aq)} + 4AsO_4^{3-}{}_{(aq)} + 6H_2O_{(l)} \rightarrow 5SO_4^{2-}{}_{(aq)} + 4As_{(s)} + 12OH^-_{(aq)}. \tag{6}$$

The solid arsenic yielded is isolated via filtration and recycled (Wang and van Genuchten, 2025).

Application

The novel treatment's application allows scientists to develop action for sustainability by solving waterway arsenic recontamination issues. Arsenic's maximum legal concentration in U.S. and Australian drinking water is 10ppb (Australian Drinking Water Guidelines, 2022; National Institute of Environmental Health Sciences, 2023), yet Figure 3 shows a river's arsenate (As(V)) concentration exceeding 10ppb over 5.8km from the recontamination source – demonstrating the importance of preventing recontamination.

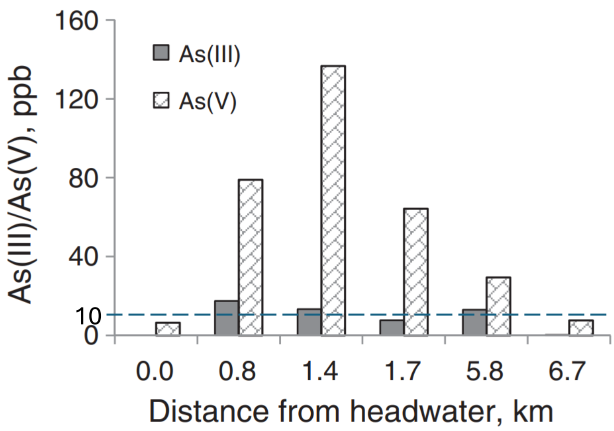

Figure 3. *The concentration of two arsenic-containing species at various distances from the source of arsenic recontamination in a river (Ilgen, Rychagov and Trainor, 2011).*

Arsenate, initially absorbed by phytoplankton, algae and aquatic plants (Zhang et al., 2022), accumulates in tissue since it is eliminated slowly. As predators consume contaminated prey, arsenic concentrations increase at higher trophic levels (Du, Zhou and Zhang, 2021), shown in Figure 4.

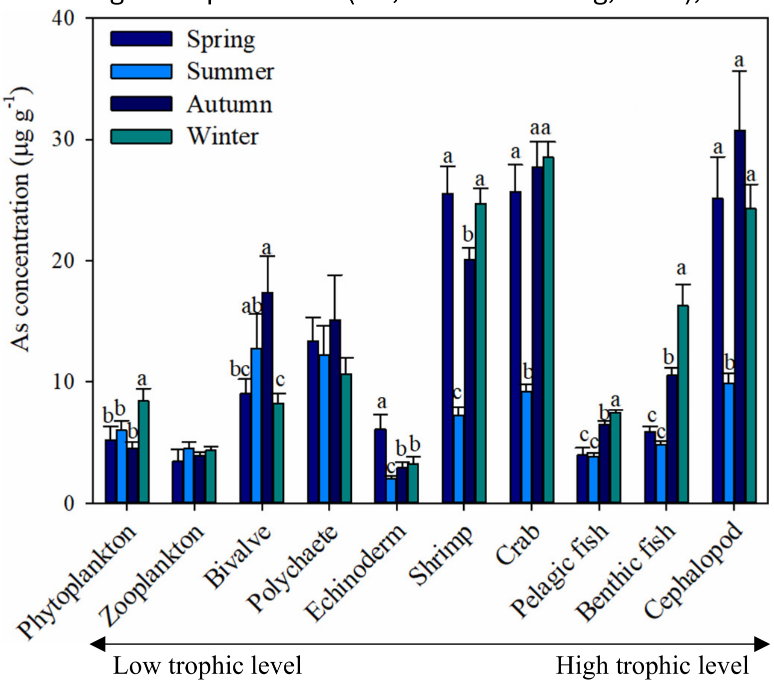

Figure 4. *Chart showing the general trend of increasing arsenic concentration in aquatic ecosystems as trophic level increases from left to right (Du, Zhou and Zhang, 2021).*

Organisms rely on adenosine triphosphate (ATP) for energy, formed from phosphate binding adenosine diphosphate (ADP). Without ATP, essential cellular processes cease, causing cell and eventually organism death (Kushnareva and Newmeyer, 2010). Arsenate, with similar size and charge to phosphate, can bind ADP to form ADP-arsenate and inhibit ATP production (Althaher and Alwahsh, 2023). This increases species extinction risk, unsustainably draining biodiverse aquatic ecosystems which provide critical services to humanity such as pharmaceuticals. For example, cytarabine, derived from Caribbean sponges, has improved long-term acute myeloid leukaemia remission rates from 10% to 80% since its implementation in 1969 (Keating et al., 1982; Willemze et al., 2014), drastically improving patients' life expectancy and quality. With over 90% of marine species currently undocumented, millions of bioactive compounds are not yet known (National Oceanic and Atmospheric Administration, 2010). Arsenic-induced extinction risks losing these opportunities – preventing afflicted individuals from accessing life-changing treatment. The new recovery method can therefore not only support ecosystem biodiversity, but also improve human life.

The knowledge behind the arsenic recovery procedures has potential to also viably recycle phosphorus, an unexpected beneficial consequence. Phosphorus is a crucial non-renewable resource in agriculture, essential in fertilisers for food production (Jasinski, 2025). With no practical substitute, its demand is expected to grow by 2–6% annually over the next decade (African Development Bank Group, 2021). The novel treatment can co-recover phosphate from wastewater due to phosphate's identical charge to arsenate (Wang and van Genuchten, 2025). At high pH, the negative iron oxyhydroxide surface electrostatically repels negative phosphate groups, desorbing phosphate which can then be precipitated using calcium salts (Christensen et al., 2022). Global wastewater contains up to 3.7 million tonnes of phosphate that can satisfy over 20% of global fertiliser demand (Kok et al., 2018), allowing the treatment to partially replace ore mining that decimates communities. For example, from 1900—1979, 22 million tonnes of phosphate were mined from Banaba Island (Faa, 2023), rendering 90% of its surface uninhabitable (Treagus, 2021). Resultantly, indigenous communities forcibly migrated from ancestral land central to their identity and spirituality (Faa, 2023), causing intergenerational trauma. The novel technique can reduce reliance on mining, mitigating similar human suffering in other regions. Additionally, 5 countries control 90% of worldwide phosphorus rock reserves (Ott and Rechberger, 2012), allowing them to manipulate market prices and limit exported supply. This creates worldwide supply volatility and unfair resource inequities, widening global developmental imbalances. Since arsenic and phosphorus occur at high groundwater concentrations in 108 countries comprising various regions (Shaji et al., 2021), the treatment enables phosphorus recycling in over half the world, reducing transport costs and securing supply. This buffers against price spikes and reduces lower-income countries' expenditure on imported fertilisers, who can redirect funds towards healthcare and education. However, phosphorus extraction efficiency (30%) is lower than arsenic (81%) (Wang and van Genuchten, 2025), providing opportunity for further innovation: if phosphorus extraction efficiency is increased, less ore needs to be mined, improving sustainability. Utilising nano-sized iron oxides, with high surface areas and hence high sorption capacities, has been proposed, though further research is required to quantify their efficacies (Ramirez et al., 2023). Overall, the unexpected phosphorus co-recovery benefit can improve resource security and sustainability.

Influence

Government policy is influencing companies to adopt the treatment by reducing its implementation's financial burden. For example, in the US, arsenic was included in the 2022 Geological Survey Critical Mineral List (Burton, 2022), and thereby incorporated into federal policy frameworks including Executive Order 14241. This order expedites environmental reviews and provides dedicated support for critical raw mineral (CRM) projects (Carl-Yoder, 2025), reducing delays and uncertainty that otherwise may prevent companies from adopting the technology. Arsenic being a CRM also provides financial incentives to companies to adopt the technology, including a 10% operational cost rebate under the Inflation Reduction Act (U.S. Department of Treasury, 2024). This reduces financial burden for companies and thus encourages adoption. Similar CRM policies exist worldwide. For example, the European Union's Critical Raw Materials Act legislates that companies must investigate and implement CRM recovery technologies (European Commission, 2023). Consequently, companies have adopted the treatment, including GEH Wasserchemie which conducts recovery operations in 61 countries (GEH Wasserchemie, n.d.). This widespread and accessible deployment allows rapid arsenic removal from waterways globally, lowering lifetime exposure. Quickly minimising arsenic exposure is particularly vital for children, as exposure significantly increases risks of cognitive impairment and depression. Chronic exposure can lower IQ by 10 points (Wang et al., 2007), lowering self-esteem and increasing depression prevalence by 400% (Tyler and Allan, 2014). In turn, depression impairs motivation and school engagement, reducing educational attainment (Sinval et al., 2024). Together, these reduce wellbeing and future workforce productivity, making timely treatment implementation critical to enable healthier, more productive lives.

Conclusion

The novel arsenic recovery method addresses critical mineral wastage by recycling groundwater arsenic and phosphorus. Its application promotes sustainable development by preventing waterway arsenic recontamination and biodiversity loss. While showing unexpected promise to recycle phosphorus via co-recovery and thereby reduce supply volatility and mining's impact on communities, phosphorus extraction efficiency is low, requiring further innovation. Government policies worldwide have reduced the financial burden of treatment implementation, influencing companies to embrace the technique.

1508 words

References

African Development Bank Group (2021). *Critical Mineral Insights: Phosphate*. [online] *African Development Bank Group*. Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development. Available at: https://www.afdb.org/sites/default/files/documents/publications/phosphate_factsheet_final_nov_21.pdf [Accessed 30 Mar. 2026].

Althaher, A.R. and Alwahsh, M. (2023). An overview of ATP synthase, inhibitors, and their toxicity. *Heliyon*, [online] 9(11), pp.e22459–e22459. doi:https://doi.org/10.1016/j.heliyon.2023.e22459.

Australian Drinking Water Guidelines (2022). *Arsenic | Australian Drinking Water Guidelines*. [online] Nhmrc.gov.au. Available at: https://guidelines.nhmrc.gov.au/australian-drinking-water-guidelines/part-5/physical-chemical-characteristics/arsenic [Accessed 1 May 2026].

Burton, J. (2022). *U.S. Geological Survey Releases 2022 List of Critical Minerals*. [online] U.S. Geological Survey. Available at: https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals [Accessed 8 Apr. 2026].

Carl-Yoder, S. (2025). *Critical Update! USGS Expands Mineral List*. [online] Brownstein. Available at: https://www.bhfs.com/insight/critical-update-usgs-expands-mineral-list/ [Accessed 8 Apr. 2026].

Chi, J., Liu, K., Wu, S., Zhang, W., Shi, Q., Fang, L. and Li, F. (2024). Dual-Ligand-Driven Dark Reactive Oxygen Species Generation on Iron Oxyhydroxides: Implications for Environmental Remediation. *Environmental Science & Technology*, [online] 58(46), pp.20751–20760. doi:https://doi.org/10.1021/acs.est.4c08791.

Christensen, M.L., Cvitanich, C., Quist-Jensen, C.A., Thau, M. and Malmgren-Hansen, B. (2022). Precipitation and recovery of phosphorus from the wastewater hydrolysis tank. *Science of the Total Environment*, [online] 813, p.151875. doi:https://doi.org/10.1016/j.scitotenv.2021.151875.

Das, B. (2017). Theoretical Study of Small Iron–Oxyhydroxide Clusters and Formation of Ferrihydrite. *The Journal of Physical Chemistry A*, [online] 122(2), pp.652–661. doi:https://doi.org/10.1021/acs.jpca.7b09470.

Du, S., Zhou, Y. and Zhang, L. (2021). The potential of arsenic biomagnification in marine ecosystems: A systematic investigation in Daya Bay in China. *Science of The Total Environment*, [online] 773, p.145068. doi:https://doi.org/10.1016/j.scitotenv.2021.145068.

European Commission (2023). *Critical Raw Materials Act*. [online] European Commission. Available at: https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en [Accessed 8 Apr. 2026].

Faa, M. (2023). Australian company Centrex under fire from Banaban islanders displaced by past phosphate mines. *ABC News*. [online] 29 Aug. Available at: https://www.abc.net.au/news/2023-08-30/australian-mining-company-centrex-banaba-atoll-pacific-kiribati/102785064 [Accessed 2 May 2026].

GEH Wasserchemie (n.d.). *GEH – the solution for sustainable clean water*. [online] GEH Wasserchemie. Available at: https://www.geh-wasserchemie.com/en/ [Accessed 7 Apr. 2026].

Gilbert-Kawai, E.T. and Wittenberg, M.D. (2014). Henderson–Hasselbalch equation. In: *Essential Equations for Anaesthesia: Key Clinical Concepts for the FRCA and EDA*. [online] Cambridge: Cambridge University Press, pp.161–162. Available at: https://www.cambridge.org/core/books/abs/essential-equations-for-anaesthesia/hendersonhasselbalch-equation/7E9C867E8BE544A656901A4270D8F9A5 [Accessed 3 May 2026].

Guo, B., Huo, H., Zhuang, Q., Ren, X., Wen, X., Yang, B., Huang, X., Chang, Q. and Li, S. (2023). Iron Oxyhydroxide: Structure and Applications in Electrocatalytic Oxygen Evolution Reaction. *Advanced Functional Materials*, [online] 33(25). doi:https://doi.org/10.1002/adfm.202300557.

Ilgen, A.G., Rychagov, S.N. and Trainor, T.P. (2011). Arsenic speciation and transport associated with the release of spent geothermal fluids in Mutnovsky field (Kamchatka, Russia). *Chemical Geology*, [online] 288(3-4), pp.115–132. doi:https://doi.org/10.1016/j.chemgeo.2011.07.010.

Jasinski, S. (2025). *Phosphate Rock Statistics and Information*. [online] National Minerals Information Centre. Available at: https://www.usgs.gov/centers/national-minerals-information-center/phosphate-rock-statistics-and-information [Accessed 30 Mar. 2026].

Keating, M.J., McCredie, K.B., Bodey, G.P., Smith, T.J., Gehan, E.A. and Freireich, E.J. (1982). Improved Prospects for Long-term Survival in Adults With Acute Myelogenous Leukemia. *JAMA*, [online] 248(19), pp.2481–2486. doi:https://doi.org/10.1001/jama.1982.03330190045029.

Kok, D.-J.D., Pande, S., van Lier, J.B., Ortigara, A.R.C., Savenije, H. and Uhlenbrook, S. (2018). Global phosphorus recovery from wastewater for agricultural reuse. *Hydrology and Earth System Sciences*, [online] 22(11), pp.5781–5799. doi:https://doi.org/10.5194/hess-22-5781-2018.

Kushnareva, Y. and Newmeyer, D.D. (2010). Bioenergetics and cell death. *Annals of the New York Academy of Sciences*, [online] 1201(1), pp.50–57. doi:https://doi.org/10.1111/j.1749-6632.2010.05633.x.

Loganathan, P., Vigneswaran, S., Kandasamy, J. and Bolan, N.S. (2014). Removal and Recovery of Phosphate From Water Using Sorption. *Critical Reviews in Environmental Science and Technology*, [online] 44(8), pp.847–907. doi:https://doi.org/10.1080/10643389.2012.741311.

Mondal, P., Bhowmick, S., Chatterjee, D., Figoli, A. and Van der Bruggen, B. (2013). Remediation of inorganic arsenic in groundwater for safe water supply: A critical assessment of technological solutions. *Chemosphere*, [online] 92(2), pp.157–170. doi:https://doi.org/10.1016/j.chemosphere.2013.01.097.

Moura, H.M. and Unterlass, M.M. (2020). Biogenic Metal Oxides. *Biomimetics*, [online] 5(2), p.29. doi:https://doi.org/10.3390/biomimetics5020029.

National Institute of Environmental Health Sciences (2023). *Arsenic*. [online] National Institute of Environmental Health Sciences. Available at: https://www.niehs.nih.gov/health/topics/agents/arsenic [Accessed 29 Mar. 2026].

National Oceanic and Atmospheric Administration (2010). *How Many Species Live in the Ocean?* [online] Noaa.gov. Available at: https://oceanservice.noaa.gov/facts/ocean-species.html [Accessed 1 May 2026].

Ott, C. and Rechberger, H. (2012). The European phosphorus balance. *Resources, Conservation and Recycling*, [online] 60, pp.159–172. doi:https://doi.org/10.1016/j.resconrec.2011.12.007.

Ramirez, P.D., Lee, C., Fedderwitz, R., Clavijo, A.R., Barbosa, D.P.P., Julliot, M., Vaz-Ramos, J., Begin, D., Le Calvé, S., Zaloszyc, A., Choquet, P., Soler, M.A.G., Mertz, D., Kofinas, P., Piao, Y. and Begin-Colin, S. (2023). Phosphate Capture Enhancement Using Designed Iron Oxide-Based Nanostructures. *Nanomaterials*, [online] 13(3), p.587. doi:https://doi.org/10.3390/nano13030587.

Satpathy, A., Wang, Q., Giammar, D.E. and Wang, Z. (2021). Intercomparison and Refinement of Surface Complexation Models for U(VI) Adsorption onto Goethite Based on a Metadata Analysis. *Environmental Science & Technology*, [online] 55(13), pp.9352–9361. doi:https://doi.org/10.1021/acs.est.0c07491.

Shaji, E., Santosh, M., Sarath, K.V., Prakash, P., Deepchand, V. and Divya, B.V. (2021). Arsenic contamination of groundwater: A global synopsis with focus on the Indian Peninsula. *Geoscience Frontiers*, [online] 12(3), p.101079. doi:https://doi.org/10.1016/j.gsf.2020.08.015.

Sinval, J., Oliveira, P., Novais, F., Almeida, C.M. and Telles-Correia, D. (2024). Exploring the impact of depression, anxiety, stress, academic engagement, and dropout intention on medical students' academic performance: A prospective study. *Journal of Affective Disorders*, [online] 368, pp.665–673. doi:https://doi.org/10.1016/j.jad.2024.09.116.

Souza, T.G.F. and Ciminelli, V.S.T. (2023). Arsenic removal and fixation by iron (oxyhydr)oxides: What is new? *Current Opinion in Environmental Science & Health*, [online] 33, p.100466. doi:https://doi.org/10.1016/j.coesh.2023.100466.

Sultan, M.W., Qureshi, F., Ahmed, S., Kamyab, H. and Yusuf, M. (2025). A Comprehensive Review on Arsenic Contamination in Groundwater: Sources, Detection, Mitigation Strategies and Cost Analysis. *Environmental Research*, [online] 265(16), p.120457. doi:https://doi.org/10.1016/j.envres.2024.120457.

Treagus, M. (2021). Flight of the frigate bird: Ocean Island, phosphate mining and Project Banaba. *Journal of Human Rights and the Environment*, [online] 12(1), pp.103–132. doi:https://doi.org/10.4337/jhre.2021.01.08.

Tyler, C.R. and Allan, A.M. (2014). The Effects of Arsenic Exposure on Neurological and Cognitive Dysfunction in Human and Rodent Studies: A Review. *Current Environmental Health Reports*, [online] 1(2), pp.132–147. doi:https://doi.org/10.1007/s40572-014-0012-1.

U.S. Department of Treasury (2024). *Inflation Reduction Act Incentives for Clean Energy Manufacturers*. [online] *U.S. Department of Treasury*. Available at: https://home.treasury.gov/system/files/8861/2024.12.12.45X_Slides%20Final.pdf [Accessed 8 Apr. 2026].

University of Texas (2013). *Henderson-Hasselbalch Equation*. [online] Utexas.edu. Available at: https://gchem.cm.utexas.edu/acidbase/index.php#buffers/hh-equation.html [Accessed 29 Apr. 2026].

University of Texas (2021). *Coordination Chemistry*. [online] Utexas.edu. Available at: https://www.geo.utexas.edu/courses/376m/coord_chem.htm [Accessed 1 May 2026].

Wang, K. and van Genuchten, C.M. (2025). Commodifying a carcinogen: Critical raw materials from arsenic-laden groundwater. *Science Advances*, [online] 11(42). doi:https://doi.org/10.1126/sciadv.adz5816.

Wang, S.-X., Wang, Z.-H., Cheng, X.-T., Li, J., Sang, Z.-P., Zhang, X.-D., Han, L.-L., Qiao, X.-Y., Wu, Z.-M. and Wang, Z.-Q. (2007). Arsenic and fluoride exposure in drinking water: children's IQ and growth in Shanyin county, Shanxi province, China. *Environmental Health Perspectives*, [online] 115(4), pp.643–647. doi:https://doi.org/10.1289/ehp.9270.

Wang, Y., Zhang, L., Guo, C., Gao, Y., Pan, S., Liu, Y., Li, X. and Wang, Y. (2022). Arsenic removal performance and mechanism from water on iron hydroxide nanopetalines. *Scientific Reports*, [online] 12(1), p.17264. doi:https://doi.org/10.1038/s41598-022-21707-1.

Willemze, R., Suciu, S., Meloni, G., Labar, B., Marie, J.-P., Halkes, C.J.M., Muus, P., Mistrik, M., Amadori, S., Specchia, G., Fabbiano, F., Nobile, F., Sborgia, M., Camera, A., Selleslag, D.L.D., Lefrère, F., Magro, D., Sica, S., Cantore, N. and Beksac, M. (2014). High-Dose Cytarabine in Induction Treatment Improves the Outcome of Adult Patients Younger Than Age 46 Years With Acute Myeloid Leukemia: Results of the EORTC-GIMEMA AML-12 Trial. *Journal of Clinical Oncology*, [online] 32(3), pp.219–228. doi:https://doi.org/10.1200/jco.2013.51.8571.

World Health Organisation (2022). *Arsenic*. [online] World Health Organisation. Available at: https://www.who.int/news-room/fact-sheets/detail/arsenic [Accessed 29 Mar. 2026].

Zhang, W., Miao, A.-J., Wang, N.-X., Li, C., Sha, J., Jia, J., Alessi, D.S., Yan, B. and Ok, Y.S. (2022). Arsenic bioaccumulation and biotransformation in aquatic organisms. *Environment International*, [online] 163, p.107221. doi:https://doi.org/10.1016/j.envint.2022.107221.

Zhu, F., Kong, L., He, M., Fang, D., Hu, X. and Peng, X. (2023). Effective reduction and recovery of As(III) and As(V) from alkaline wastewater by thiourea dioxide: Efficiency and mechanism. *Water Research*, [online] 243, p.120355. doi:https://doi.org/10.1016/j.watres.2023.120355.