Extremophile Algae Power Arsenic Cleanup

Cyanidiophyceae can detoxify and immobilize arsenic under oxygen-free conditions.

Arsenic contamination in groundwater poses severe health risks worldwide, especially in regions where anaerobic (oxygen-depleted) conditions promote the dissolution of toxic arsenite [As(III)]. Conventional treatment methods often struggle in these reducing environments. A new study published in *Chemical Engineering Journal* demonstrates a promising biological method using extremophilic red microalgae (Cyanidiophyceae) to bio-oxidize iron and immobilize arsenic under anaerobic conditions.[1] The research led by Yu-Ting Liu (National Chung Hsing University) and Yen-Lin Cho (National Sun Yat-sen University), in collaboration with scientists from the NSRRC, reveals that Cyanidiophyceae species *Cyanidium caldarium* (Cc) and *Galdieria partita* (Gp) can oxidize ferrous iron [Fe(II)] to ferric iron [Fe(III)] anaerobically, forming reactive Fe(III) (oxyhydr)oxides that efficiently trap arsenic. These findings open a new route for biological arsenic remediation in oxygen-depleted environments such as aquifers and sediments. To elucidate how these extremophilic algae achieve such efficient detoxification, the team employed a suite of synchrotron-based techniques, including X-ray absorption spectroscopy (XAS) at **TLS 17C1** and **TPS 44A**, X-ray fluorescence (XRF) nanoprobe mapping at **TPS 23A**, transmission X-ray microscopy (TXM) at **TLS 01B1**, and Fourier-transform infrared (FTIR) microspectroscopy at **TLS 14A1**.

Under strictly anaerobic conditions, both Cc and Gp were able to convert over 96.8% of sorbed Fe(II) into Fe(III) within hours. The resulting Fe(III) hydroxides served as active sites for arsenite adsorption and coprecipitation. When pre-loaded with Fe, the algae showed 45–61% higher As(III) sorption capacity compared with unmodified cells,

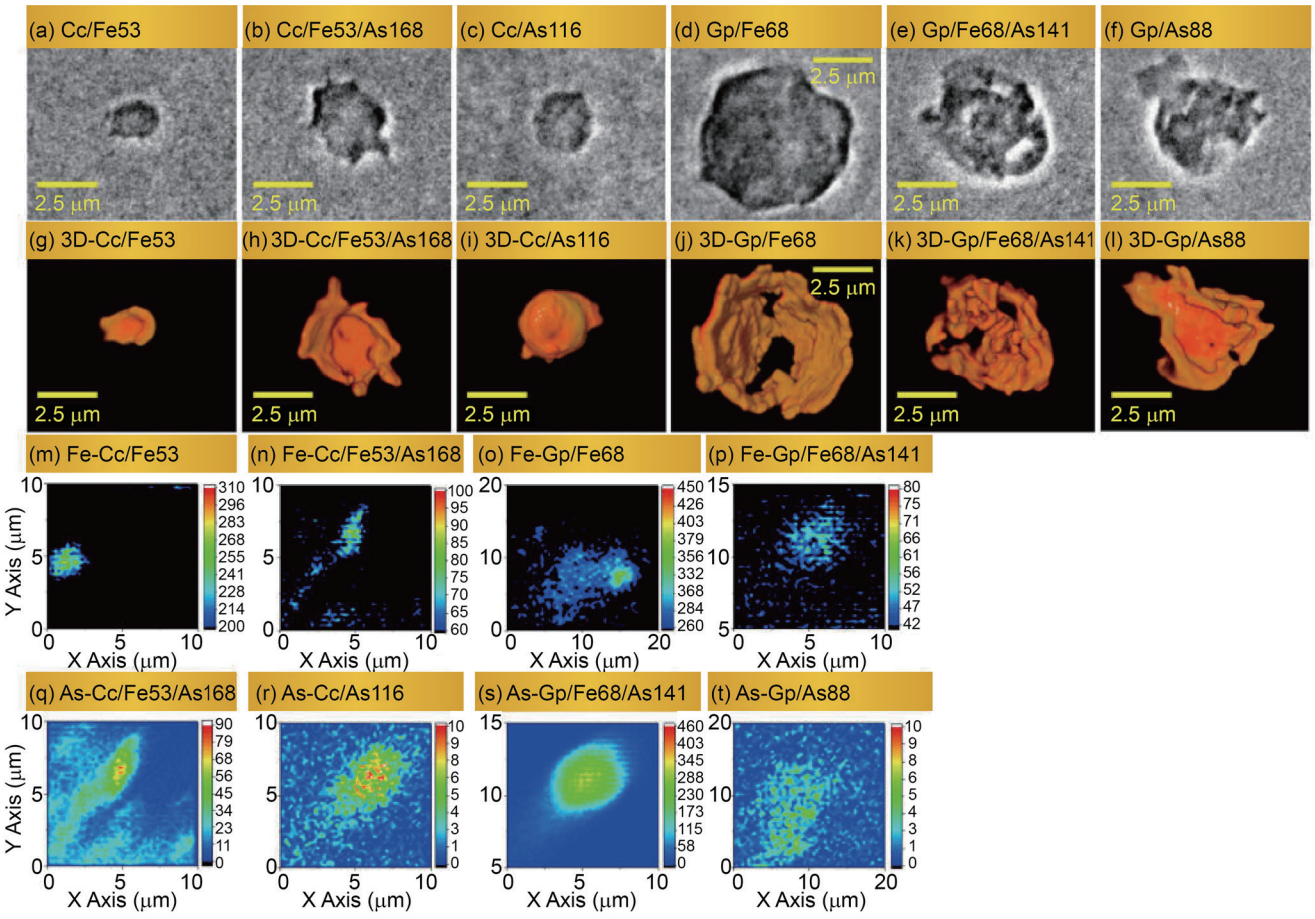

Fig. 1: (a–f) 2D images, (g–l) 3D tomography images, (m–p) Fe distribution, and (q–t) As distribution in Cc, Gp, and Fe-loaded Cc and Gp collected during Fe(II) sorption kinetics experiments and upon acquisition of As(III) sorption isotherms. The numbers after Fe and As indicate the sorption amounts in mg g^{-1}. The distributions of Fe and As metals in the 2D and 3D images were shown as darker and lighter areas, respectively. The specific Fe and As distributions (m–t) in cells were determined by nano (XRF) mapping. [Reproduced from Ref. 1]

achieving up to 168 mg g^{-1} arsenic uptake—far exceeding most inorganic sorbents under similar conditions. XAS analysis confirmed that these Fe(III) phases were primarily amorphous hydroxides and Fe–polysaccharide complexes, both known for high affinity toward arsenic. The Fe–As association observed by XRF mapping demonstrated that Fe localized along the cell periphery, while As was distributed across cell walls and interiors, indicating cooperative surface and intracellular processes.

Despite similar Fe oxidation abilities, the two microalgae displayed distinct arsenic detoxification pathways, as revealed by synchrotron XAS and FTIR spectroscopy. Cc utilized an intracellular detoxification mechanism. In Cc, XAS identified As(III)–cysteine complexes [As(III)–cys] formed inside cells, while FTIR showed structural protein changes (altered α-helix/β-strand ratios), confirming biochemical adaptation to metal stress. This strategy allowed Cc to internalize and stabilize arsenic within the cytoplasm. By contrast, Gp adopted a surface-mediated oxidation mechanism. Fe(II) bio-oxidation and As(III) oxidation to less toxic As(V) occurred concurrently, with the oxidized species bound to extracellular polysaccharides. This indicates that Gp relies on its cell-wall chemistry and extracellular enzymes for As detoxification.

Figure 1 presents the 3D tomography (TXM) and nano-XRF elemental mapping that directly reveal how Cc and Gp distribute Fe and As after Fe(II) loading and As(III) sorption. The Fe signal forms a clear ring around both Cc and Gp cells, demonstrating that Fe(II) taken up by the algae is rapidly oxidized at or near the cell wall. This visualizes the exact location where Fe(III) phases form under anaerobic conditions. Additionally, arsenic XRF signals overlap with Fe-rich zones, directly supporting the conclusion that newly formed Fe(III) minerals act as the dominant sinks for As(III). This co-localization provides spatial evidence that Fe(III) bio-oxidation is the key step enabling the high As uptake measured in the sorption experiments. In Gp, Fe and As signals remain largely at the cell surface, consistent with its surface-based As oxidation and extracellular polysaccharide binding. In Cc, arsenic signals penetrate deeper into the cell, supporting the intracellular As(III)–cysteine complexation pathway revealed by XAS and FTIR. By visually capturing Fe–As distribution at the single-cell level, Cyanidiophyceae enhance arsenic removal because their anaerobic Fe(II) bio-oxidation generates highly reactive Fe(III) phases that efficiently immobilize As(III).

This study demonstrates that Cyanidiophyceae can function as natural, self-regenerating bio-oxidizers capable of coupling iron cycling and arsenic immobilization even in oxygen-free systems—conditions typical of contaminated aquifers. By converting Fe(II) to Fe(III) and forming stable Fe(III) hydroxides that co-precipitate arsenic, the algae offer a sustainable route for *in-situ* groundwater cleanup. Moreover, their resilience, ease of cultivation, and micrometer-scale size enable practical recovery through simple microfiltration, making them viable for engineered treatment systems. The strong Fe–As binding confirmed by synchrotron XAS also ensures minimal risk of secondary metal release, further supporting their use in long-term environmental applications.

The combined biological and synchrotron findings highlight how extremophilic algae, armed with ancient iron-oxidizing genes, can be harnessed as eco-friendly bio-oxidizers for arsenic removal. Under anaerobic conditions, Cc and Gp exhibit complementary mechanisms that together create a highly effective, resilient system for As(III) detoxification. Through advanced X-ray spectroscopy and microscopy, the research team unveiled the hidden interplay between Fe redox cycling, As sequestration, and cellular adaptation. This research not only deepens our understanding of microbial metal metabolism but also showcases nature-inspired solutions for global water challenges. (Reported by Yu-Jong Wu)

This report features the work of Yen-Lin Cho, Yu-Ting Liu, and their co-workers published in Chem. Eng. J. ***523****, 168303 (2025).*

TPS 23A X-ray Nanoprobe
- XRF
- Materials Science, Soft Matters

TLS 01B1 X-ray Microscopy
- TXM
- Materials Science

TLS 14A1 IR Microscopy
- IR mapping
- Materials Science, Life science

TPS 44A Quick-scanning X-ray Absorption Spectroscopy

TLS 17C1 EXAFS
- XAS
- Materials Science

Reference

1. N. A. T. Than, L. C. Hsu, Y.-H. Chen, K. Huangmee, C.-C. Wang, H. Y. Teah, Y.-M. Tzou, Y.-L. Cho, Y.-T. Liu, Chem. Eng. J. **523**, 168303 (2025).