Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.36834

Multiscale Characterization of Arsenic Spatial Distribution and Bioaccessibility in Mine Waste Particles

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Arsenic (As) is a toxic trace metalloid that can harm both humans and the environment due to its carcinogenic nature. Anthropogenic activities such as metal mining can mobilize arsenic when enriched in fine-grained mine wastes. Prolonged exposure to low-level arsenic poses risks to populations near abandoned mine sites, primarily through ingestion and inhalation pathways. Accurate quantification of arsenic bioaccessibility is therefore critical for long-term risk assessment and remediation efforts. While bioaccessibility is influenced by bulk factors such as total concentration, surface area, and particle size, particle-scale spatial distribution remains under-studied due to challenges in quantification and resolution, despite its potential influence on arsenic release. This study evaluates the effectiveness of arsenic spatial distribution as an indicator of changes in bioaccessibility over time, emphasizing the development of novel analytical workflows to resolve particle-scale heterogeneity.

Simulated gastric fluid (SGF) extractions of ground and unground mine waste samples were conducted to simulate ingestion and analyzed via ICP-OES to calculate percent arsenic bioaccessibility. Synchrotron-based micro X-ray fluorescence (μXRF) maps collected at the Stanford Synchrotron Radiation Lightsource were analyzed before and after simulated ingestion to quantify spatial distribution patterns within individual particles. An image segmentation and geospatial workflow was applied to calculate relative arsenic enrichment and depletion at defined radial distances within particles (**Figure 1**), and statistical classification methods were used to characterize Fe:As association patterns. Integrating bioaccessibility measurements with high-resolution spatial mapping, the aim of this study is to demonstrate an analytical approach to legacy metal pollution with mechanistic indicators of mobility and exposure, offering a framework for prioritizing contaminated mine sites.

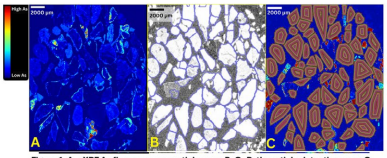

Figure 1. A, μXRF As fluorescence particle map; B, QuPath particle detection map; C, QGIS particle map with concentric 50 μm rings.