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Critical mineral immobilization by an alkaline microbial community for advanced recovery and remediation of ultramafic mine leachate

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The demand for critical minerals, particularly those required for clean energy technology, will accelerate as the world seeks to reduce global CO_2 emissions. Legacy mine wastes often contain critical minerals that were not recovered during historic mining operations, providing a valuable secondary source for reprocessing. Ultramafic mine tailings, such as those produced from Cu-Ni-platinum group element mines, are ideal resources for advanced recovery as coupled metal immobilization and CO_2 sequestration can be microbially mediated in tailings ponds on site. A stratified microbial community can induce the precipitation of carbonate and sulfide minerals through the metabolic production of alkalinity and H_2S, as well as through the production of extracellular polymeric substances (EPS), which provide binding sites for divalent cations.

This study evaluated coupled phototrophic microbial mats and anaerobic sediment inoculated with sulfate-reducing bacteria in a 38 L bioreactor experiment system. Aqueous chemistry mimicked ultramafic leachate containing Cr (15 mg L^{-1}), Mn (25 mg L^{-1}), and Ni (45 mg L^{-1}), with elevated Mg concentrations (2500 mg L^{-1}). Sampling ports along the side of the bioreactor allowed for diurnal collection of water samples at each mat layer over the 16-week experiment. Results indicate recovery of >90% for each metal by week 16, with Cr, Fe, and Ni reaching ~100%. By week 16, Ni concentrations were below Canadian regulatory limits for effluent under Canada's Metal and Diamond Mining regulations. Microbial community analysis (16S amplicon sequencing) revealed a relative reduction in the abundance of cyanobacteria, suggesting changing microbial dynamics may impact precipitates formed during critical mineral recovery. Scanning electron microscopy and energy dispersive spectroscopy indicated Ca- and Mg- carbonates primarily formed in the mat layers, while micron-scale Fe-Ni-S precipitates were observed in the sediment. Preliminary synchrotron-based X-ray fluorescence imaging data (BioXAS-Imaging, Canadian Light Source) of week 16 thin sections indicated co-located metals (Cr, Mn, Ni) in with the Mg-platelets and acicular grains in the microbial mat and within the precipitate formed along sediment grain boundaries. The removal effectiveness suggests the promising role of microbes in metal attenuation from ultramafic leachates and informs the understanding of biogeochemical controls influencing the targeted advanced recovery of critical minerals.