ECOMINE: A BIOREGENERATIVE ISRU PLATFORM FOR LUNAR MINERAL EXTRACTION. P. Flores[1], N. Doherty Garcia [2], M. Beck[3], J. Lee[4], A. Abbud-Madrid[5], and C. Chamberlain[6], [1]Space Lab Technologies, 5455 Spine Rd, Ste ME, Boulder, CO, 80301, USA pame@spacelabtech.com, [2]Space Lab Technologies, 5455 Spine Rd, Ste ME, Boulder, CO, 80301, USA naiara@spacelabtech.com, [3]Space Lab Technologies, 5455 Spine Rd, Ste ME, Boulder, CO, 80301, USA matthew@spacelabtech.com, [4]Colorado School of Mines, 1500 Illinois St, Golden, CO, 80401, USA jaeheonlee@mines.edu, [5]Colorado School of Mines, 1500 Illinois St, Golden, CO, 80401, USA aabbudma@mines.edu,[6]Space Lab Technologies, 5455 Spine Rd, Ste ME, Boulder, CO, 80301, USA chris@spacelabtech.com.

Introduction: Establishing a sustained human presence on the Moon will require extensive surface infrastructure and reliable access to primary materials. In-situ resource utilization (ISRU) offers a pathway to obtain structural and industrial minerals directly from lunar regolith. These materials can support the fabrication of numerous lunar infrastructure components, including rover parts, habitat frames, radiation-protective panels, and solar panels, thereby reducing launch mass and reliance on Earth-supplied materials. Lunar soils contain abundant oxides including SiO_2, Al_2O_3, FeO, TiO_2, MgO, and CaO [1], [2]. However, conventional terrestrial mining approaches such as pyrometallurgy and hydrometallurgy require high temperatures, large quantities of chemical reagents, and significant energy inputs, making them poorly suited for lunar operations [3], [4].

Biomining offers a lower-energy alternative to conventional mineral extraction by leveraging microbial metabolism to mobilize metals from solid substrates [5]. Through processes such as acidolysis, redoxolysis, and complexolysis, microorganisms produce metabolites that promote the dissolution and complexation of metal ions from mineral phases [6]. While industrial biomining on Earth is commonly based on chemolithotrophic microorganisms that oxidize sulfide minerals, lunar regolith is dominated by oxides and silicates with limited sulfide availability. Under these conditions, heterotrophic microorganisms capable of secreting organic acids provide a more suitable pathway for mineral dissolution. Organic acids such as citric, oxalic, and gluconic acid can protonate mineral surfaces and form soluble complexes with metal ions, enabling mobilization of elements such as Al, Fe, Ti, and Si from regolith [7], [8]. However, heterotrophic bioleaching typically requires a continuous supply of organic carbon to sustain microbial metabolism, which presents logistical challenges for space-based applications and motivates the development of regenerative systems capable of producing these substrates in situ.

EcoMine™ is a bioregenerative biomining platform designed to extract valuable minerals from lunar regolith while regenerating its own consumables in a closed-loop biological system.

Bioregenerative Mining: EcoMine integrates biological and physicochemical processes creating a regenerative mineral extraction facility. The system couples five primary subsystems: a photobioreactor (PBR), an aerobic fermentation reactor (AFR), a bioleaching reactor (BLR), a selective mineral recovery unit (MIN), and a waste treatment reactor (WTR) (Figure 1).

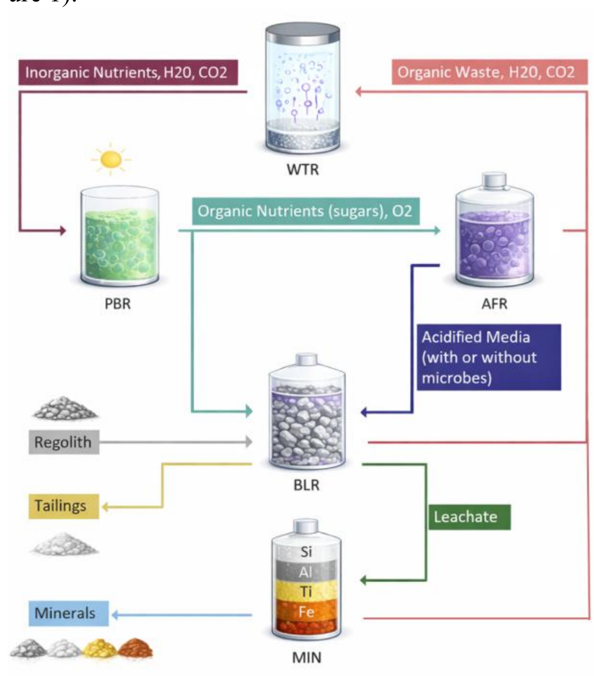

Figure 1. Integrated Regenerative Biomining Process. Flow diagram linking the photobioreactor (PBR), aerobic fermentation reactor (AFR), bioleaching reactor (BLR), waste treatment reactor (WTR), and selective mineral recovery (MIN) units. Arrows indicate direction of movement.

Photoautotrophic microorganisms in the PBR convert light and CO_2 into oxygen and organic carbon substrates. These substrates support heterotrophic microorganisms in the AFR that produce organic acids through aerobic metabolism. The acidified media is then introduced to the BLR where proton-mediated dissolution and ligand-assisted complexation mobilize metals such as Al, Ti, Fe, and Si from lunar regolith.

Dissolved metals are subsequently processed in the MIN subsystem through solvent extraction, stripping, and precipitation to recover purified mineral products. Wastewater streams from the process are treated in the WTR using UV-assisted TiO_2 photocatalysis, which mineralizes organic contaminants into CO_2, water, and inorganic nutrients. These regenerated streams are returned to the PBR, closing the carbon, nutrient, and water loops and enabling sustained operation with minimal resupply.

Current design development and results: Recent efforts focus on integration of the regenerative reactor loop (PBR, AFR, and WTR), long-term metabolic stability of microbial subsystems, and optimization of mineral recovery pathways. Preliminary solvent extraction experiments demonstrate high extraction efficiencies for Ti and Fe from model sulfate and chloride solutions Figure 2).

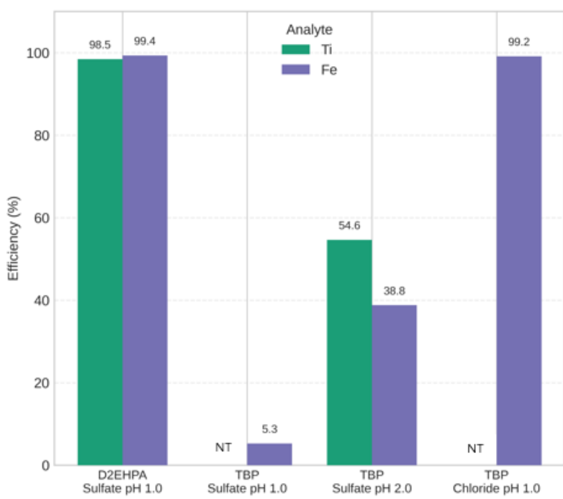

Figure 2. Preliminary extraction efficiencies for Ti and Fe in sulfate and chloride matrices. NT: not tested yet.

D2EHPA achieved near-quantitative extraction of Ti (98.47%) and Fe (99.36%) from sulfate solutions at pH 1.0, indicating strong complexation and efficient phase transfer under highly acidic conditions. This behavior aligns with the known affinity of acidic organophosphorus extractants for tri- and tetravalent metal ions [9], [10]. TBP, in contrast, exhibited limited Fe extraction from sulfate media at pH 1.0 (5.28%). Increasing the aqueous pH to 2.0 improved extraction to 54.65% for Ti and 38.8% for Fe, likely due to shifts in metal speciation and reduced proton competition that enhance solvating interactions with TBP. However, performance remained inferior to D2EHPA under comparable sulfate conditions. A strong matrix effect was observed in chloride systems, where TBP extracted ferric chloride with 99.15% efficiency at pH 1.0, demonstrating the significant influence of aqueous phase composition on extraction behavior. While ongoing work is focused on completing tests and standardizing optimal extraction conditions in sulfate and chloride matrices, future studies will evaluate extraction performance in biologically generated leachates, which is a more complex chemical environment.

The WTR is intended to completely mineralize organic contaminants and support closed-loop water, inorganic nutrient, and CO_2 recovery within the EcoMine system. The current objective is to evaluate the feasibility and characterize the performance of TiO_2 photocatalytic oxidation for the wastewater generated in the EcoMine system. To enable this experimental validation, a brassboard reactor has been designed in which TiO_2 serves as the photocatalytic surface. UV illumination excites the TiO_2 surface and drive photocatalytic reactions. The proprietary reactor configuration will allow assessment of contaminant degradation efficiency and operational compatibility with a regenerative life-support architecture.

Conclusion: EcoMine demonstrates the feasibility of a biologically driven, closed loop ISRU architecture capable of recovering useful minerals from low grade lunar regolith while regenerating key consumables. Ongoing design and experimental validation aim to demonstrate the integration of these bioregenerative processes within a unified system. This approach reduces energy demand, minimizes reliance on hazardous reagents, and supports autonomous resource production for future lunar and planetary missions.

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