ECOMINE: A BIOREGENERATIVE APPROACH TO LUNAR REGOLITH MINING.

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Introduction: NASA's plans to establish a sustained Lunar presence for scientific research, Mars mission preparation, and a thriving commercial Lunar economy will require significant surface infrastructure. The use of in situ resources provides an alternative source of rare Earth minerals for terrestrial use as well as minerals for Lunar use enabling a more economical and sustainable approach to constructing this infrastructure. Lunar regolith contains an abundance of Si and Al in anorthite, Fe and Ti in ilmenite, magnesium [1], and REEs (La, Nd, Sc, Ce) in mare regolith and KREEP rock [2]. However, traditional Earth mining processes are not economically feasible on the moon, due to high energy demands, labor needs, high mass transport costs for consumable reagents (like acids and alkalis), lower ore grade, and potential environmental and safety impacts. EcoMine™ is a bioregenerative mining facility designed for use on the Lunar surface and adaptable for asteroid, Mars, or Earth utilization. It combines a closed-loop biomining process that continuously regenerates consumables (e.g., acids, nutrients, O_2, water) with an autonomous, self-powered, bioprocessing facility for commercial operations. The use of biological organisms for mineral leaching is environmentally safer with lower energy demands than chemical mineral mining and it generally has improved extraction efficiency for low-grade ores, like lunar regolith. The Space Lab® EcoMine™ facility can integrate with other infrastructure (like regolith excavation) and is mobile, which minimizes the distance (and time) between excavation, processing, and disposal of regolith.

Bioleaching: Bioleaching uses microorganisms to extract economically important elements from rocks, sediment, and even anthropogenic waste (like electronic components), mimicking natural biogeochemical processes on Earth (like rock weathering). Direct or indirect interaction with microorganisms of ore surfaces dissolve the minerals of interest. The mechanisms of bioleaching include acidolysis, redoxolysis, complexolysis, and bioaccumulation. In acidolysis, heterotroph organisms produce organic acids (e.g. acetic, oxalic, lactic, and formic acids) through the metabolism of carbon sources. The organic acids then protonate the metal ions in the ore to dissolve them. In redoxolysis, microorganisms secrete enzymes that catalyze redox reactions with metal elements. In complexolysis, the extracellular polymeric substance (EPS) on the membrane of microorganisms induces the chelation and complexation of metal ions. Lastly, bioaccumulation refers to the absorption and concentration of the metal ions inside the microbial cells [3].

Bioleaching is often more efficient and cost effective (albeit slower) at element extraction than abiotic processes that use harsh chemicals like cyanide, especially for low grade ore [4], [5]. Commercial scale biomines on Earth most commonly employ chemolithoautotrophs to extract metals from pyrite and other solid oxides [6], but heterotrophic microorganisms, as *Penicillium*, *Aspergillus*, *Bacillus*, and even cyanobacteria, are also highly effective [7], [8], [9]. Typical bioleaching chemolithoautotrophs require a form of sulfur (or iron) for energy which is not consistently available in lunar regolith. This means that acidolysis with heterotrophic organisms is more appropriate for space applications, but this requires an organic carbon source for energy to generate organic acids. These organisms solubilize minerals with the secreted organic acids as follows (example for citric acid):

a) $H_3(C_6H_5O_7)$ (citric acid) (aq) + H_2O (l) ↔ H_3O^+ (aq) + $H_2(C_6H_5O_7)^-$ (aq)

b) 3 $CaAl_2Si_2O_8$ (anorthite) (s) + 8 H_3O^+ (aq) + 8 $H_2(C_6H_5O_7)^-$ (aq) ↔ 6 $AlC_6H_5O_7$ (aq) + $Ca_3(C_6H_5O_7)_2$ (aq) + 6 SiO_2 (aq) + 20 H_2O (l)

Bioregenerative approach: The main processes in the EcoMine™ closed-loop regenerative biomining approach (Figure 1) involve: *i*) the production of oxygen and organic carbon sources (e.g. glucose and/or sucrose) by a reactor of photoautotrophic organisms (photobioreactor) harvesting energy from light and carbon dioxide through photosynthesis, *ii*) the consumption of oxygen and carbon sources by a reactor of aerobic heterotroph organisms (aerobic fermentation reactor) producing organic acids and carbon dioxide as part of their metabolism byproducts, *iii*) the use of the acidified media (with or without heterotrophs) to be in contact with the lunar regolith for bioleaching the minerals of interest, and *iv*) the return of carbon dioxide and other inorganic nutrients recovered from the aerobic fermentation reactor and the bioleaching reactor to the photobioreactor where they will be used again.

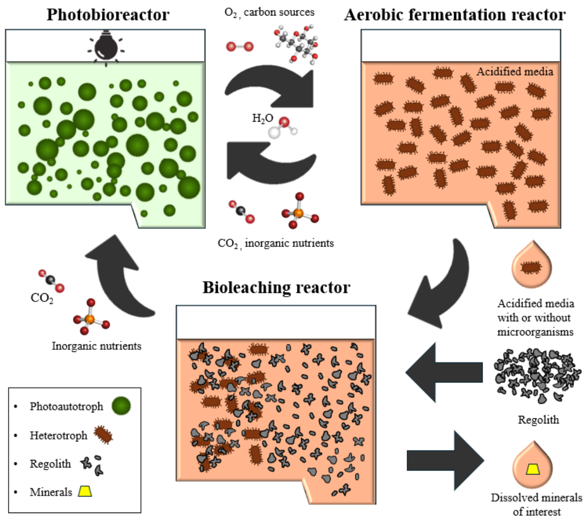

Figure 1. Bioregenerative biomining processes of EcoMine™.

Space Lab® presents an overview and concept of operations of the EcoMine™ bioregenerative mining process, preliminary design of the facility, and preliminary results of the closed-loop bioleaching efforts. EcoMine™ is a major step towards a viable, sustainable Lunar economy with several innovative features transferable to Earth applications.

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