EcoMine™: A Bioregenerative Approach to Lunar Regolith Mining

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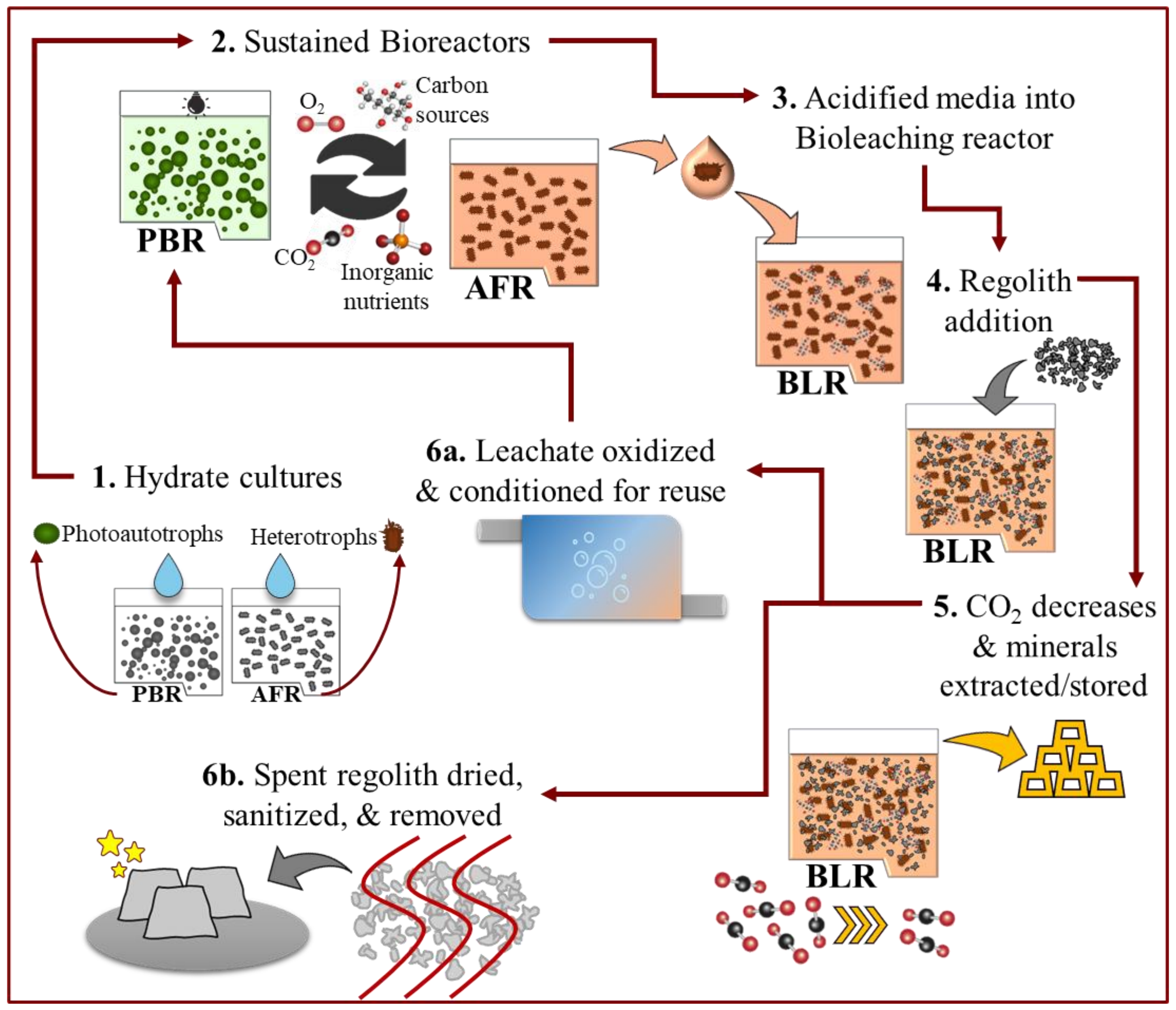
INTRODUCTION

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 as well as for Lunar use enabling a more economical and sustainable approach. Lunar regolith contains an abundance of Si and Al in anorthite, Fe and Ti in ilmenite, Mg [1], and Rare Earth Elements (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, transport costs for consumable reagents (like acids and alkalis), lower ore grade, and potential environmental and safety impacts. **Space Lab®** presents an overview of **EcoMine™**, a bioregenerative mining facility (Fig.1) 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, H_2O) with an autonomous, self-powered, bioprocessing facility for commercial operations. Its use of biological organisms for mineral leaching is environmentally safer, with lower energy demands than chemical mineral mining and has improved extraction efficiency for low-grade ores, like Lunar regolith.



2. Sustained Bioreactors

O_2

Carbon sources

PBR

CO_2

Inorganic nutrients

AFR

3. Acidified media into Bioleaching reactor

4. Regolith addition

BLR

BLR

1. Hydrate cultures

Photoautotrophs

Heterotrophs

PBR

AFR

6a. Leachate oxidized & conditioned for reuse

5. CO_2 decreases & minerals extracted/stored

6b. Spent regolith dried, sanitized, & removed

BLR

Figure 1: EcoMine™ Concept of Operations. (1) Operations start with the hydration of stock cultures. **(2)** Once cultures bloom, they exchange products (O_2, CO_2, inorganic nutrients and organic carbon sources like glucose/sucrose) to use as nutrients in a bioregenerative cycle, generating sustained growth of photoautotrophs in the Photobioreactor (**PBR**) and heterotrophs in the Aerobic Fermentation Reactor (**AFR**). **(3, 4)** Then media aliquots from AFR are moved to the Bioleaching Reactor (**BLR**) to allow for acidification and incubation with Lunar regolith to start bioleaching of minerals of interest. **(5)** Once microorganisms decrease CO_2 production, spent regolith is separated to recover the minerals of interest from the leachate. **(6a, b)** The remaining leachate gets oxidized and reconditioned to be reused by the PBR, while the tailings are treated to be taken out of the facility.

For Methods & References visit QR Code →

RESULTS

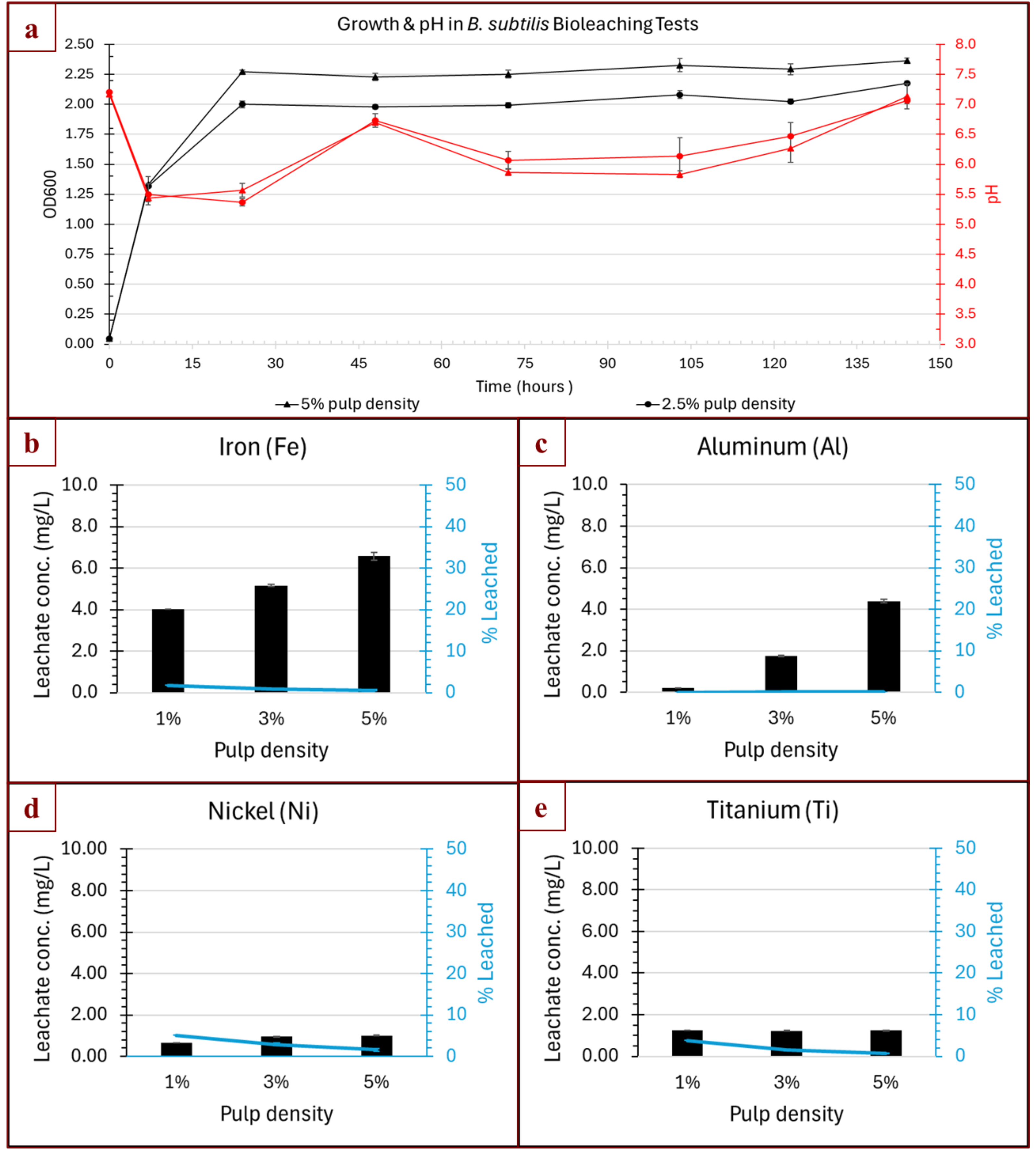


Figure 2: *B. subtilis* heterotrophic bioleaching efficiencies & metal recovery (a) Growth curves (black lines) and corresponding pHs (red lines). *B. subtilis* did not show signs of toxicity when exposed to Lunar highland's regolith simulant (LHS-1). Media acidification was unaffected by pulp densities. **(b – e)** All leaching efficiencies (blue lines) were low (< 5%), with 1% pulp density offering slightly higher leaching efficiency.

Metal	Space Lab *B. subtilis* (1% LHS-1)	Giese et al. 2019 [3] *B. subtilis* (1% Ni-laterite ore)	Space Lab *A. niger* (1% LHS-1)	Qu et al. 2019 [4] *Acetobacter sp.* (2% red mud)	Netpae & Suckley 2020 [5] *A. niger* (Ni-Cd batteries)
Fe	D: 7 E: 1.77% R: 4.02mg/L	N/R	D: 7 E: 30.86% R: 70.04 mg/L	D:10 E:~32.5% R: N/R	N/R
Al	D: 7 E: 0.02% R: 0.21mg/L	N/R	D: 7 E: 8.46% R: 83.68 mg/L	D: 10 E: ~54% R: N/R	N/R
Ni	D: 7 E: 5.12% R: 0.67 mg/L	D: 7 E: 1.9% R: N/R	D: 7 E: 7.03% R: 0.91mg/L	N/R	D: 14 E: 65% R: 375.78 mg/g
Ti	D: 7 E: 3.78% R: 1.25mg/L	N/R	D: 7 E: 27.87% R: 9.22mg/L	D: 10 E: 45% R: N/R	N/R

Table 1: Comparison of bioleaching efficiencies & metal recovery values. Comparison of Space Lab experimental values and reported theoretical values. D: Bioleaching duration in days, E: Leaching efficiency, R: Metal recovery (Space Lab: [leachate] = [tail] – [head]; mg/L), N/R: Not reported. Si was not able to be accurately determined in our leachate due to its high instability in aqueous solution.

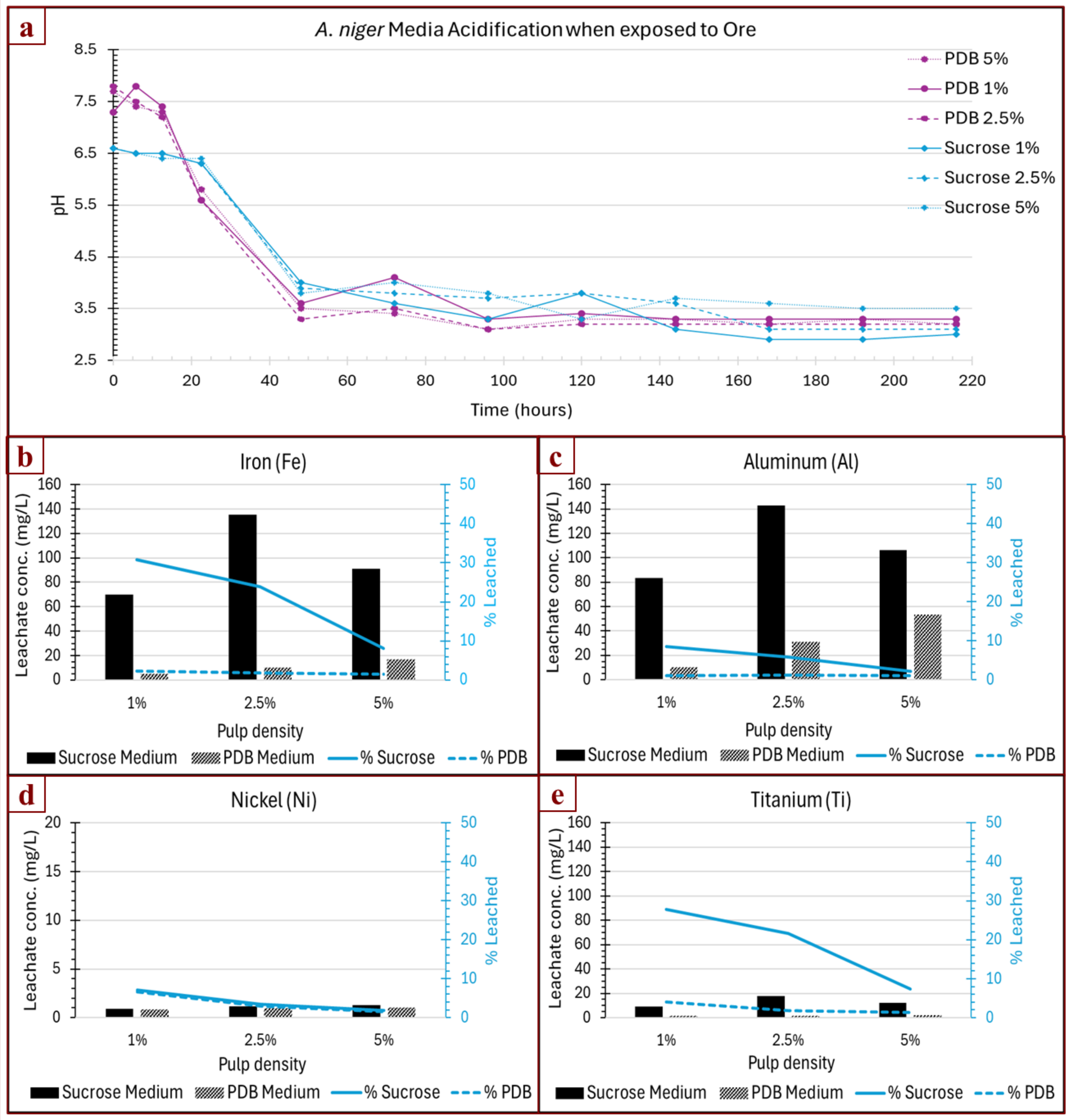
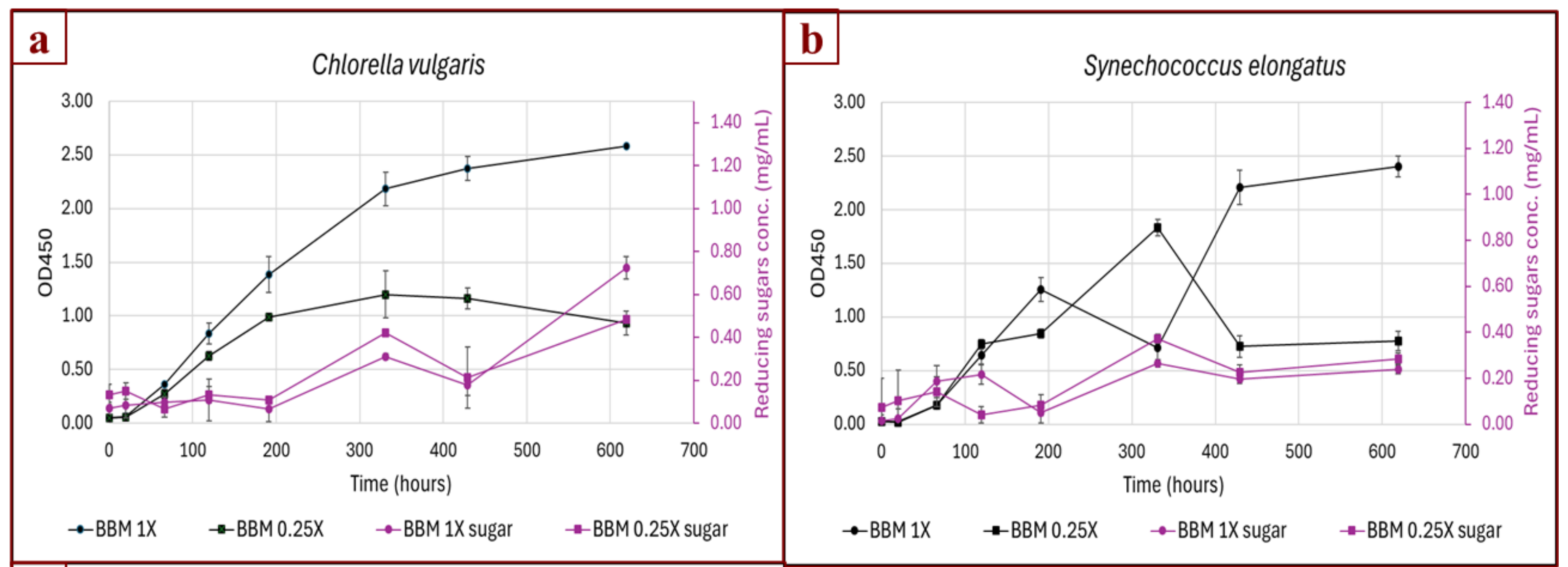


Figure 3: *A. niger* heterotrophic bioleaching efficiencies & metal recovery. (a) pH of growth media, PDB (pink lines) or Sucrose (blue lines). Media acidification was unaffected by pulp densities. **(b – e)** 2.5% pulp density yielded highest metal recovery (black bars). Leaching efficiencies (blue lines) of all metals (except Ni), on Sucrose medium, were 1.25x to 13x higher than with PDB.



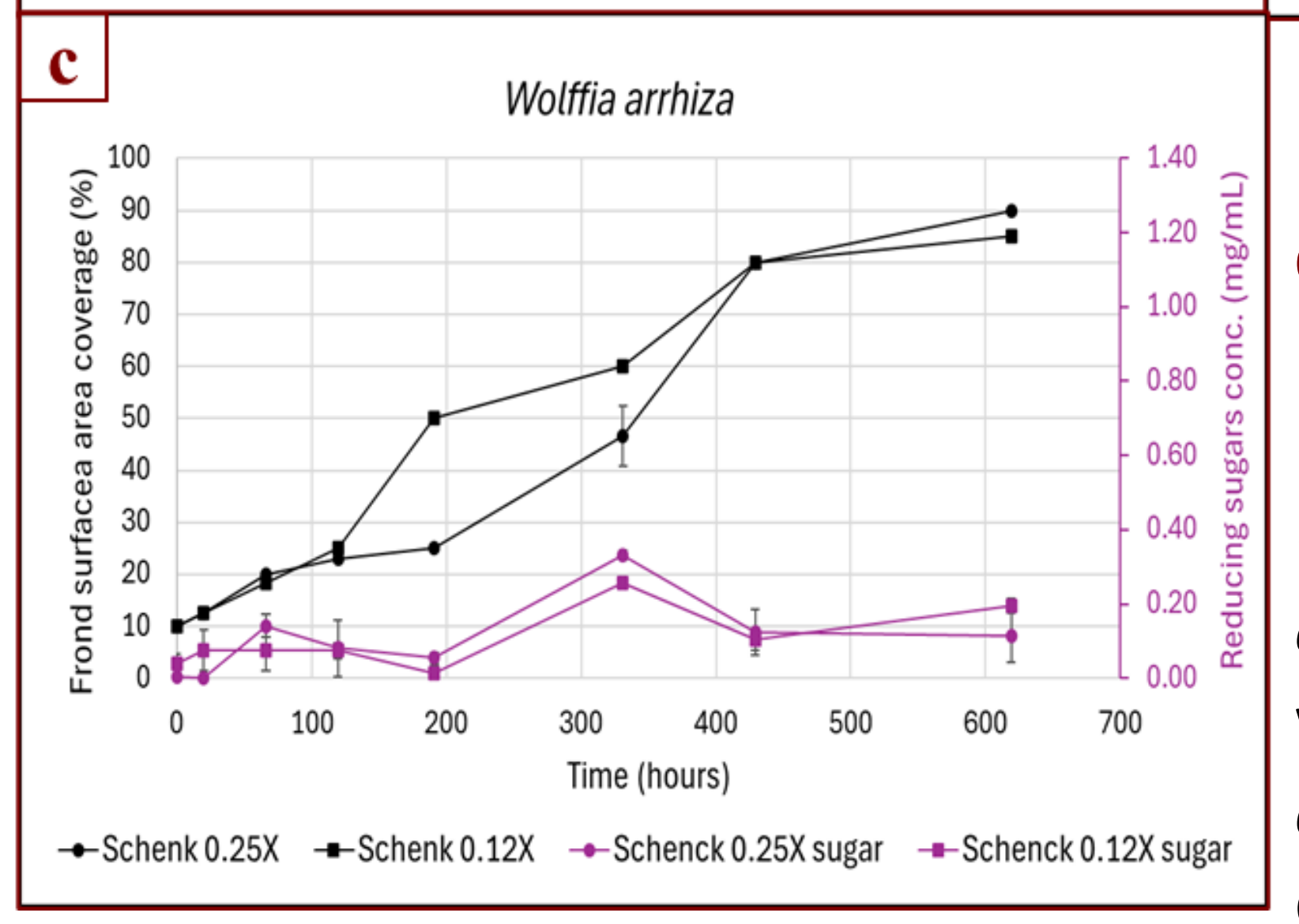


Figure 4: Photoautotrophs showed highly variable sugar production dependent on organisms and media concentration. (a – c) Growth (black lines) and sugar production (pink lines). **(a)** *C. vulgaris* and **(b)** *S. elongatus* highest sugar production was detected under 0.25X BBM. **(c)** *W. arrhiza* highest sugar production was detected under 0.25X Schenk & Hildebrandt medium.

FUTURE DIRECTIONS

1. Optimize leaching conditions of heterotrophs for best metal leaching;
2. Optimize conditions for best sugar production from photoautotrophs;
3. Optimize metal recovery from liquid media;
4. Test closed-loop efficiency of photoautotrophs feeding bioleachers (heterotrophs) with regolith addition.