

Bacterial Biomining Rare Earth Elements in Abandoned Coal Mine Drainage: Solubilization and Sequestration

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Background Information

Abandoned Coal-Mine Drainage (AMD)

Critical Minerals (CM) / Rare Earth Elements (REE)

Acidogenesis Isolates that Reduce Manganese

Abandoned Mine Drainage (AMD)

Coal Mining in Pennsylvania

Unregulated 1700s → 1945

Legacy mines ~11,000 mines



<https://wwhistoryonview.org/catalog/004468>

Sulfuric Acid → Solubilize Metals → Mn/CM/REE

Treat AMD in Passive Remediation Systems

Precipitate AMD Waste as Solids



Critical Minerals and Metals (CMMs) and Rare Earth Elements (REEs)

Modern Tech REE Demand ↑ Globally

Rechargeable Batteries, Electric Motors, Wind Turbines, Superconductors, Lasers, Optical Fibers, Aerospace Alloys

Conventional REE Extraction

High Temp & Harsh Chemicals = Toxic Waste

AMD as a Source of REEs

AMD REEs ~10,000 > non-AMD waters (Vo 2024)

REEs + Mn in AMD solids (Hedin, Stuckman 2024)

1 H Hydrogen 1.01																												2 He Helium 4.00							
3 Li Lithium 6.94		4 Be Beryllium 9.01																5 B Boron 10.81		6 C Carbon 12.01		7 N Nitrogen 14.01		8 O Oxygen 16.00		9 F Fluorine 19.00		10 Ne Neon 20.18							
11 Na Sodium 22.99		12 Mg Magnesium 24.31																13 Al Aluminum 26.98		14 Si Silicon 28.09		15 P Phosphorus 30.97		16 S Sulfur 32.07		17 Cl Chlorine 35.45		18 Ar Argon 39.95							
19 K Potassium 39.10		20 Ca Calcium 40.08		21 Sc Scandium 44.96		22 Ti Titanium 47.87		23 V Vanadium 50.94		24 Cr Chromium 52.00		25 Mn Manganese 54.94		26 Fe Iron 55.85		27 Co Cobalt 58.93		28 Ni Nickel 58.69		29 Cu Copper 63.55		30 Zn Zinc 65.39		31 Ga Gallium 69.72		32 Ge Germanium 72.61		33 As Arsenic 74.92		34 Se Selenium 78.96		35 Br Bromine 79.90		36 Kr Krypton 83.80	
37 Rb Rubidium 85.47		38 Sr Strontium 87.62		39 Y Yttrium 88.91		40 Zr Zirconium 91.22		41 Nb Niobium 92.91		42 Mo Molybdenum 95.94		43 Tc Technetium (98)		44 Ru Ruthenium 101.07		45 Rh Rhodium 102.91		46 Pd Palladium 106.42		47 Ag Silver 107.87		48 Cd Cadmium 112.41		49 In Indium 114.82		50 Sn Tin 118.71		51 Sb Antimony 121.76		52 Te Tellurium 127.60		53 I Iodine 126.90		54 Xe Xenon 131.29	
55 Cs Cesium 132.91		56 Ba Barium 137.33		57 La Lanthanum 138.91		58 Ce Cerium 140.12		59 Pr Praseodymium 140.91		60 Nd Neodymium 144.24		61 Pm Promethium (145)		62 Sm Samarium 150.36		63 Eu Europium 151.96		64 Gd Gadolinium 157.25		65 Tb Terbium 158.93		66 Dy Dysprosium 162.50		67 Ho Holmium 164.93		68 Er Erbium 167.26		69 Tm Thulium 168.93		70 Yb Ytterbium 173.04		71 Lu Lutetium 174.97			
87 Fr Francium (223)		88 Ra Radium (226)		89 Ac Actinium (227)		90 Th Thorium 232.04		91 Pa Protactinium 231.04		92 U Uranium 238.03		93 Np Neptunium (237)		94 Pu Plutonium (244)		95 Am Americium (243)		96 Cm Curium (247)		97 Bk Berkelium (247)		98 Cf Californium (251)		99 Es Einsteinium (252)		100 Fm Fermium (257)		101 Md Mendelevium (258)		102 No Nobelium (259)		103 Lr Lawrencium (262)			

Mn Reducing Bacteria (MnRB)

Produce Acid (Acidogenesis)

Isolate	16S <i>rrn</i> Identity
AV20	90% <i>Bacillus cereus</i>
AV21	98% <i>Corynebacterium</i> sp.▽
AV22	83% <i>Bacillus</i> sp.
AV23	90% <i>Bacillus thuringiensis</i>
AV24	98% <i>Corynebacterium</i> sp.
KB7	100% <i>Bacillus pseudomyoides</i> ▽
JR07	100% <i>Bacillus mycoides</i> ▽
Sterile	NA

▽Whole genome sequencing (WGS)

*Differential Manganese Reduction Media KMnO_4

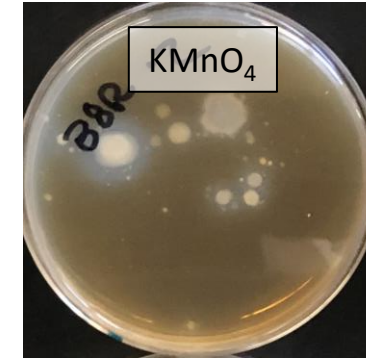
+Differential Manganese Reduction Media MnO_2

♦Acid Production Determined by Phenol Red/pH probe/TSI Slants

NA = Not applicable

Mn Reducing Bacteria (MnRB)

Produce Acid (Acidogenesis)



Isolate	16S <i>rrn</i> Identity	Reduces KMnO ₄ *
AV20	90% <i>Bacillus cereus</i>	+
AV21	98% <i>Corynebacterium sp.</i> ▽	+
AV22	83% <i>Bacillus sp.</i>	+
AV23	90% <i>Bacillus thuringiensis</i>	+
AV24	98% <i>Corynebacterium sp.</i>	+
KB7	100% <i>Bacillus pseudomycoides</i> ▽	+
JR07	100% <i>Bacillus mycoides</i> ▽	+
Sterile	NA	-

▽Whole genome sequencing (WGS)

*Differential Manganese Reduction Media KMnO₄

+Differential Manganese Reduction Media MnO₂

♦Acid Production Determined by Phenol Red/pH probe/TSI Slants

NA = Not applicable

Mn Reducing Bacteria (MnRB)

Produce Acid (Acidogenesis)

Isolate	16S <i>rrn</i> Identity	Reduces KMnO_4^*	Reduces MnO_2^+
AV20	90% <i>Bacillus cereus</i>	+	+
AV21	98% <i>Corynebacterium sp.</i> [▽]	+	+
AV22	83% <i>Bacillus sp.</i>	+	+
AV23	90% <i>Bacillus thuringiensis</i>	+	+
AV24	98% <i>Corynebacterium sp.</i>	+	+
KB7	100% <i>Bacillus pseudomycooides</i> [▽]	+	+
JR07	100% <i>Bacillus mycooides</i> [▽]	+	+
Sterile	NA	-	-

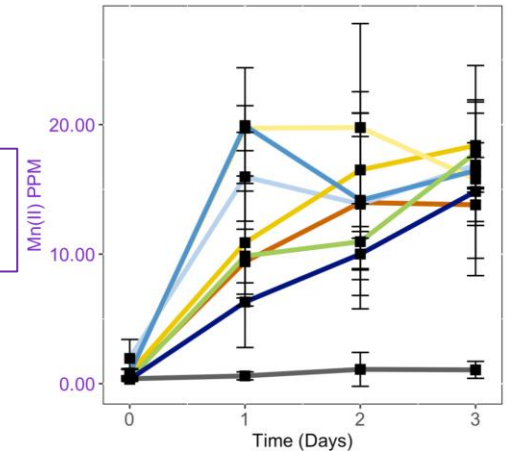
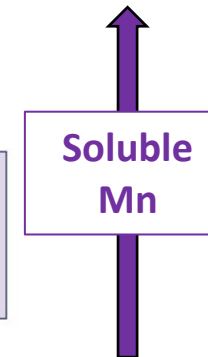
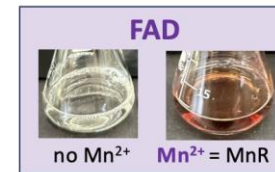
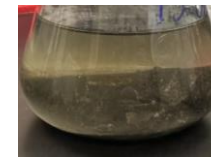
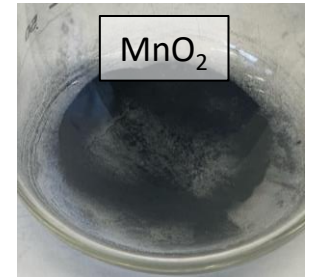
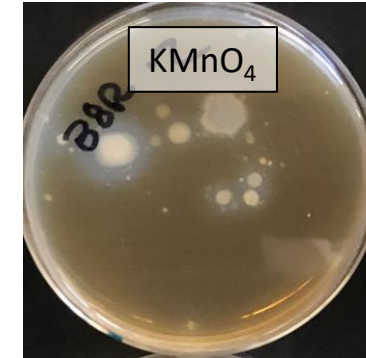
[▽]Whole genome sequencing (WGS)

*Differential Manganese Reduction Media KMnO_4

+Differential Manganese Reduction Media MnO_2

†Acid Production Determined by Phenol Red/pH probe/TSI Slants

NA = Not applicable



Mn Reducing Bacteria (MnRB)

Produce Acid (Acidogenesis)

Isolate	16S <i>rrn</i> Identity	Reduces KMnO_4^*	Reduces MnO_2^+	Produces Acid [†]
AV20	90% <i>Bacillus cereus</i>	+	+	+
AV21	98% <i>Corynebacterium sp.</i> [▽]	+	+	+
AV22	83% <i>Bacillus sp.</i>	+	+	+
AV23	90% <i>Bacillus thuringiensis</i>	+	+	+
AV24	98% <i>Corynebacterium sp.</i>	+	+	+
KB7	100% <i>Bacillus pseudomyoides</i> [▽]	+	+	+
JR07	100% <i>Bacillus mycoides</i> [▽]	+	+	+
Sterile	NA	-	-	-

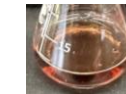
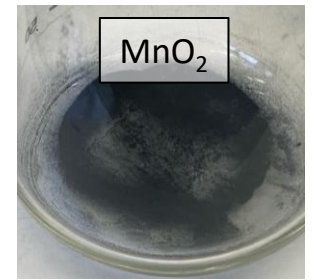
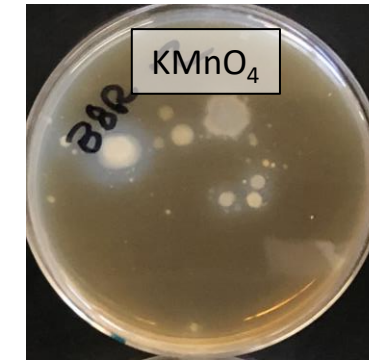
[▽]Whole genome sequencing (WGS)

*Differential Manganese Reduction Media KMnO_4

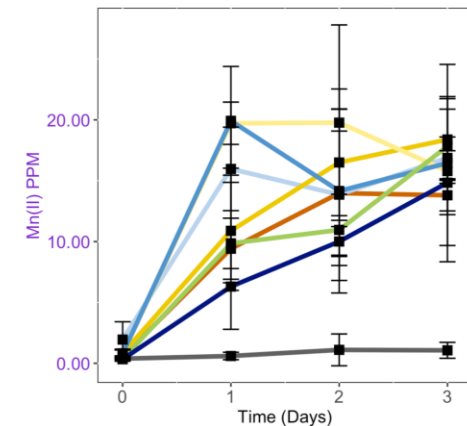
[†]Differential Manganese Reduction Media MnO_2

[‡]Acid Production Determined by Phenol Red/pH probe/TSI Slants

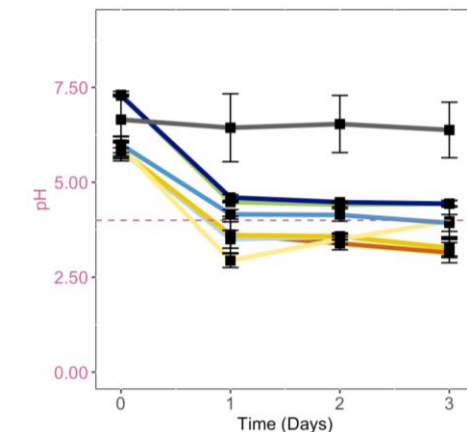
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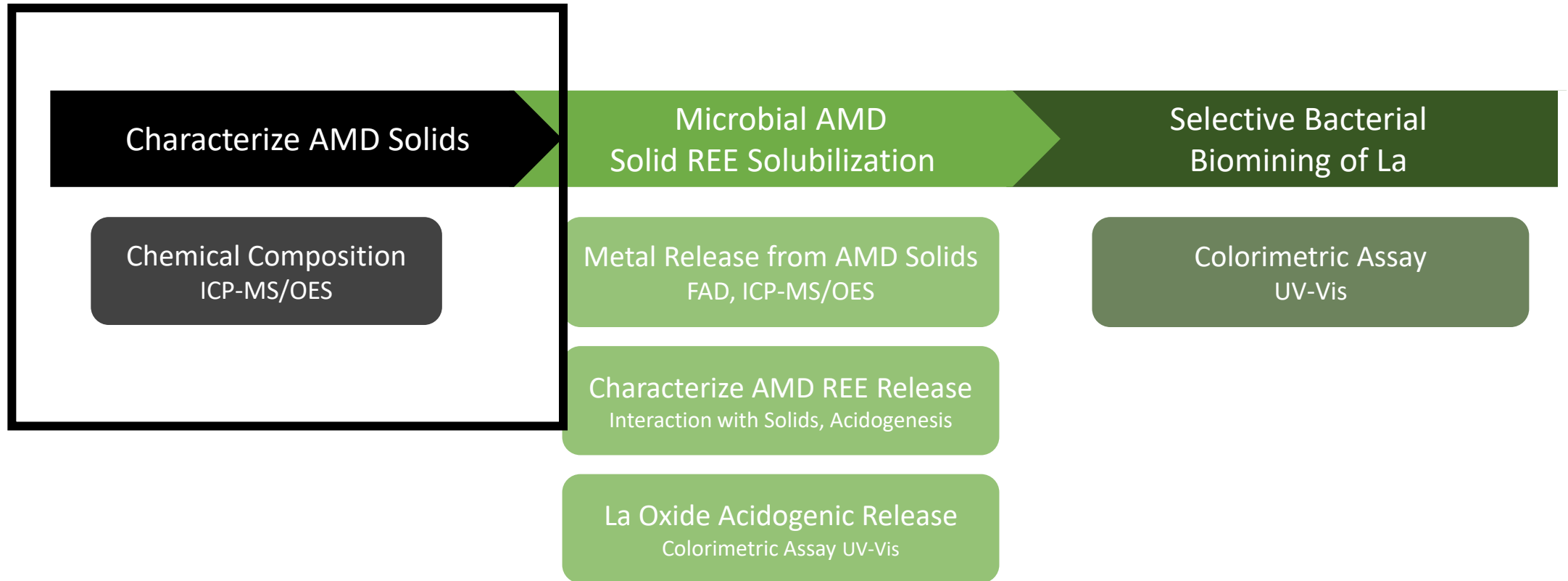


Soluble Mn



pH Drop





AMD Systems to Target for Biomining

Recommended by NETL based on previous work by Ben Hedin, PhD

Wingfield Pines



Sterrett



Kentucky
Hollow



Scootac



Glasgow



Chemical Comparisons of AMD Solids



Wingfield
Pines

Sterrett

Kentucky
Hollow

Scootac

Glasgow

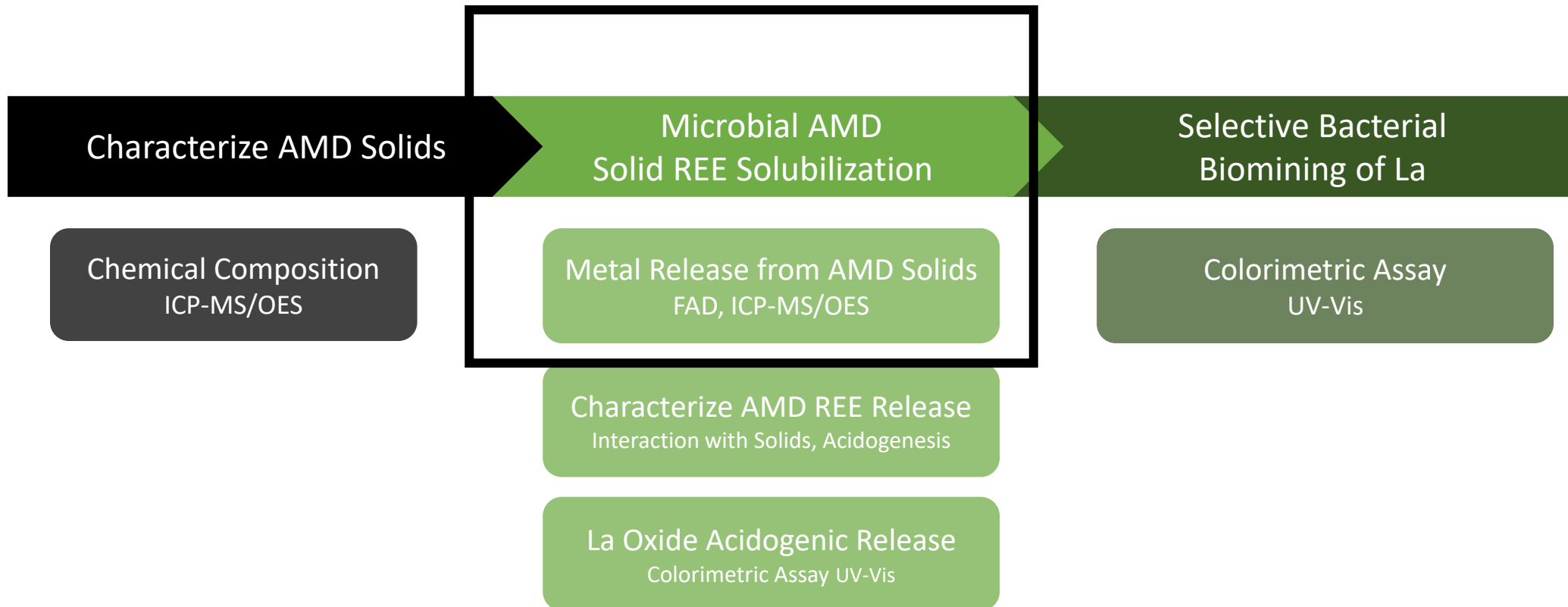
	Mn	Fe	Al	Li	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	As	Zr	Sn	Sb	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	U
WP	3434.00	81,110	39,500	34	9	61	68	17	35	7	128	12	15	121	4	1	21	22	48	6	22	5	1	4	1	4	1	2	0	2	0	2
St	78,727	93,623	78,010	104	7	36	27	1,187	917	52	1,888	13	31	57	1	1	272	89	259	36	173	55	14	71	11	55	10	27	3	19	3	11
KH	14,627	50,640	91,280	61	15	91	66	613	858	151	954	18	61	73	2	1	144	69	246	33	151	41	9	45	7	31	6	15	2	10	1	11
Sc	108,900	3,294	19,388	60	3	3	18	3,962	4,746	59	7,794	20	7	14	6	0	261	80	131	26	110	27	7	41	6	36	8	20	2	13	2	1
G	13,750	6,805	9,555	9	2	4	14	912	149	41	207	4	2	6	2	0	28	11	26	4	16	4	1	5	1	5	1	2	0	1	0	0

ICP-MS & ICP-OES

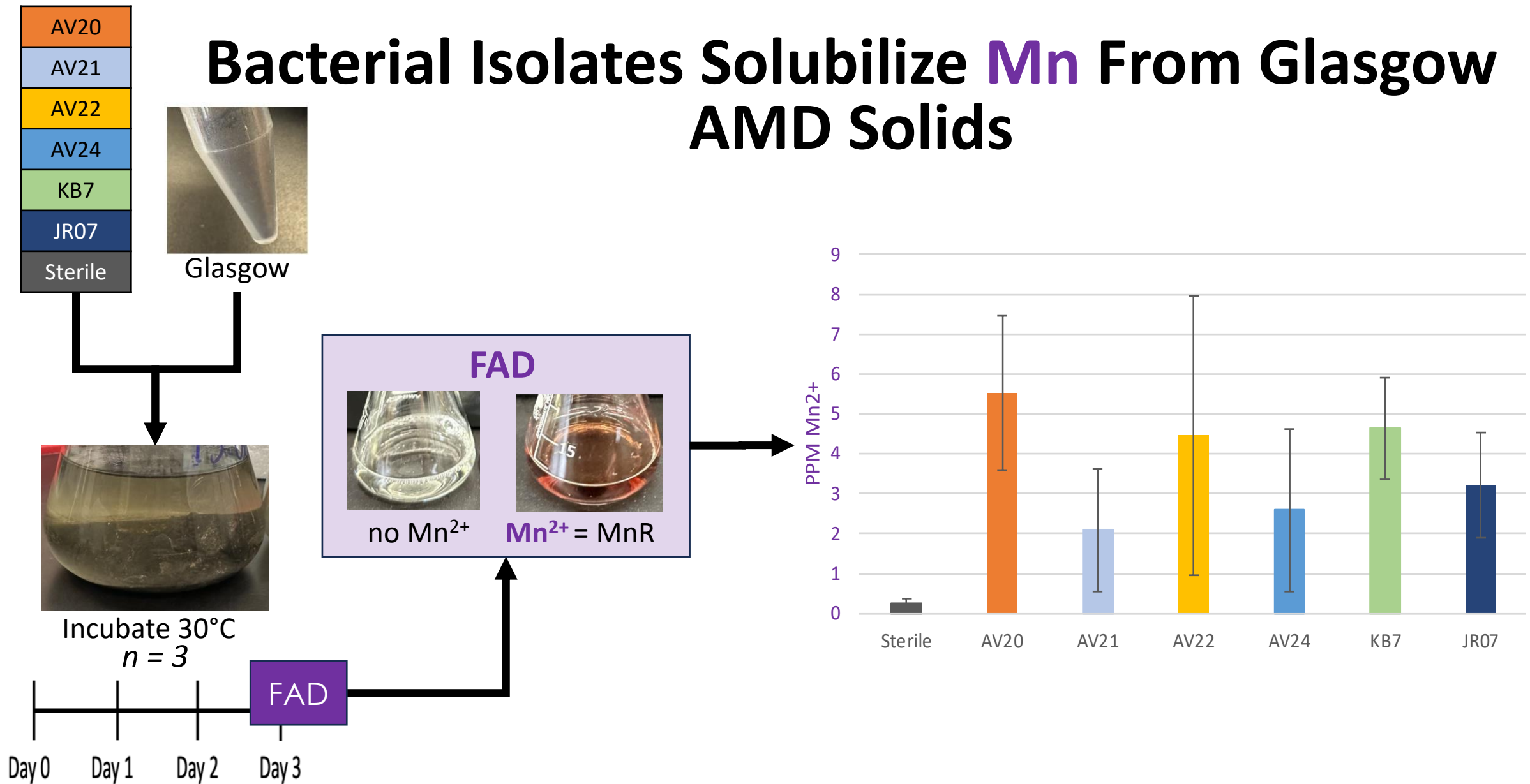
PPM values reported

High Low

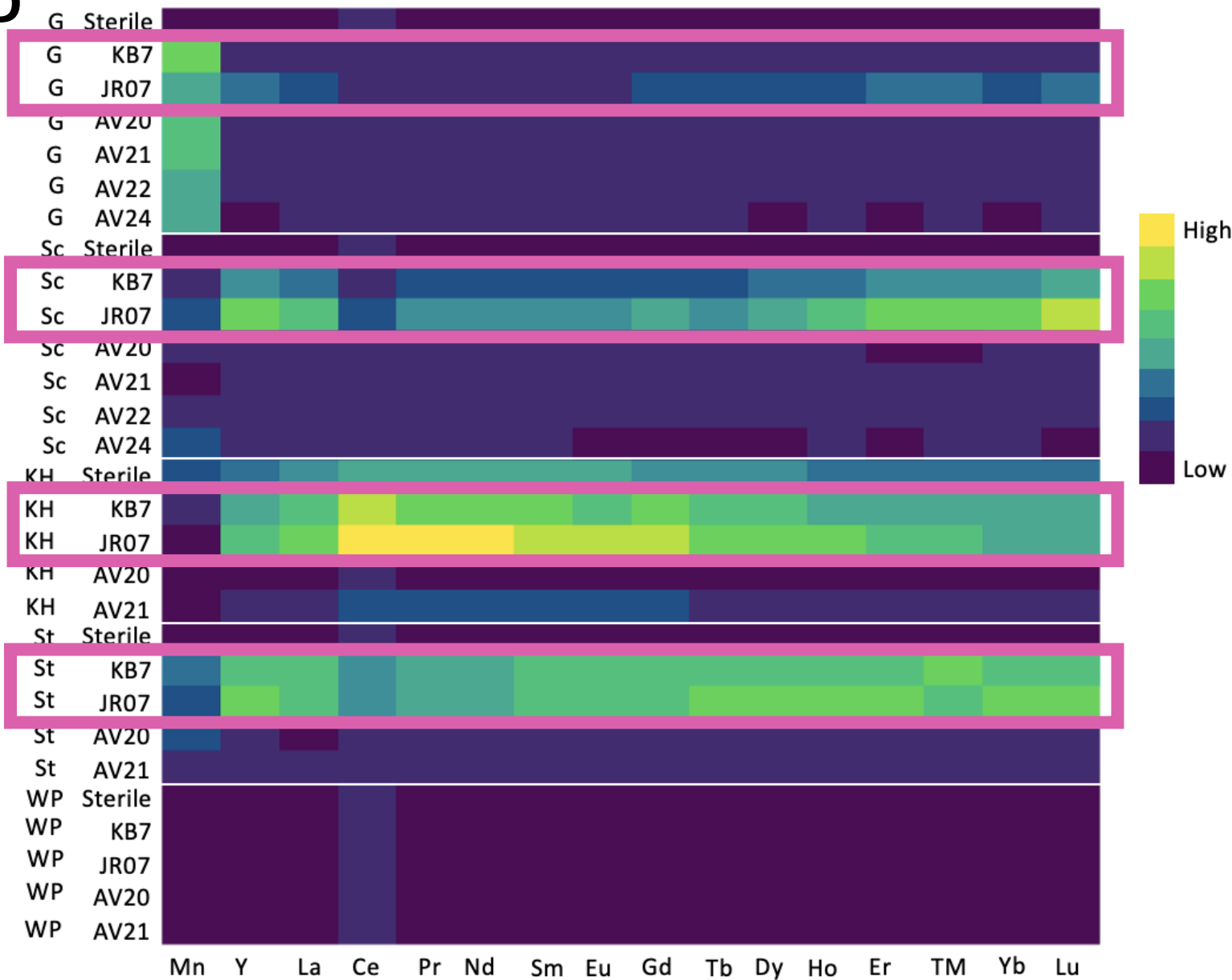
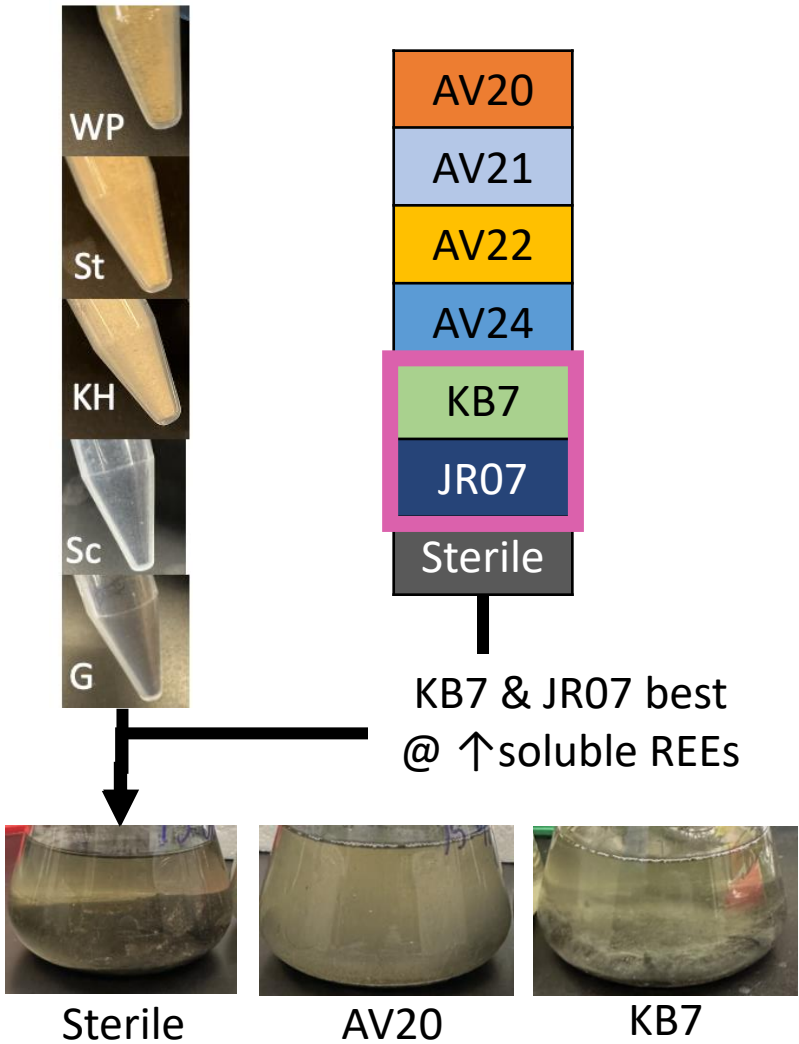
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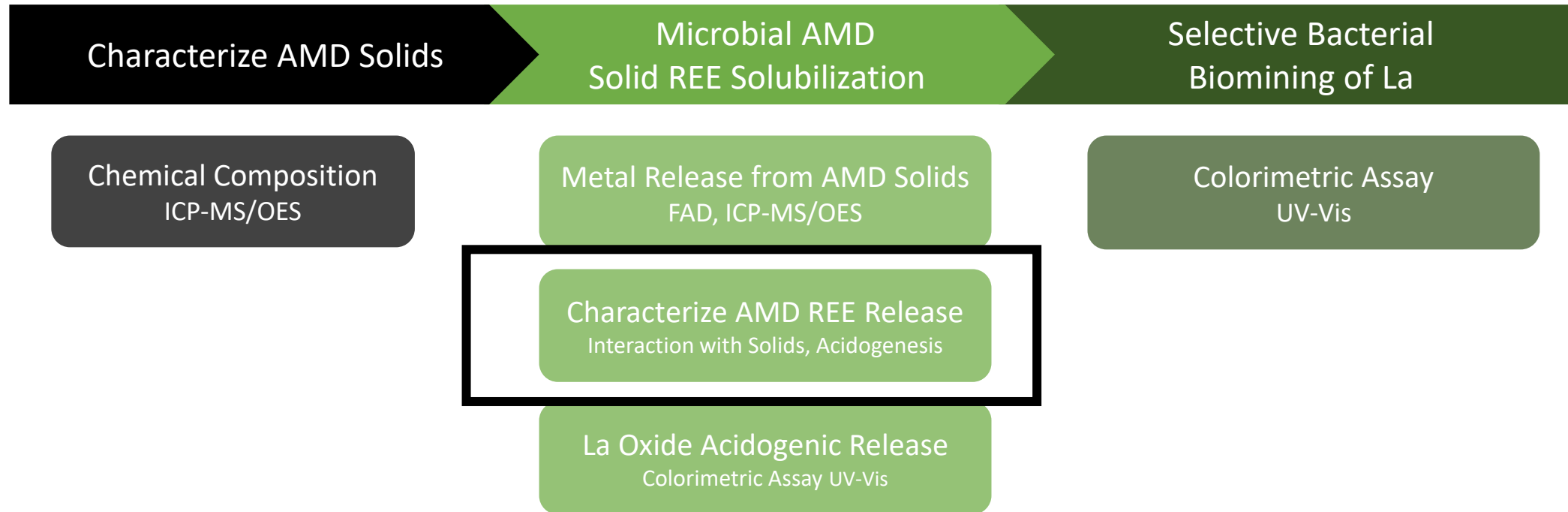


Bacterial Isolates Solubilize Mn From Glasgow AMD Solids

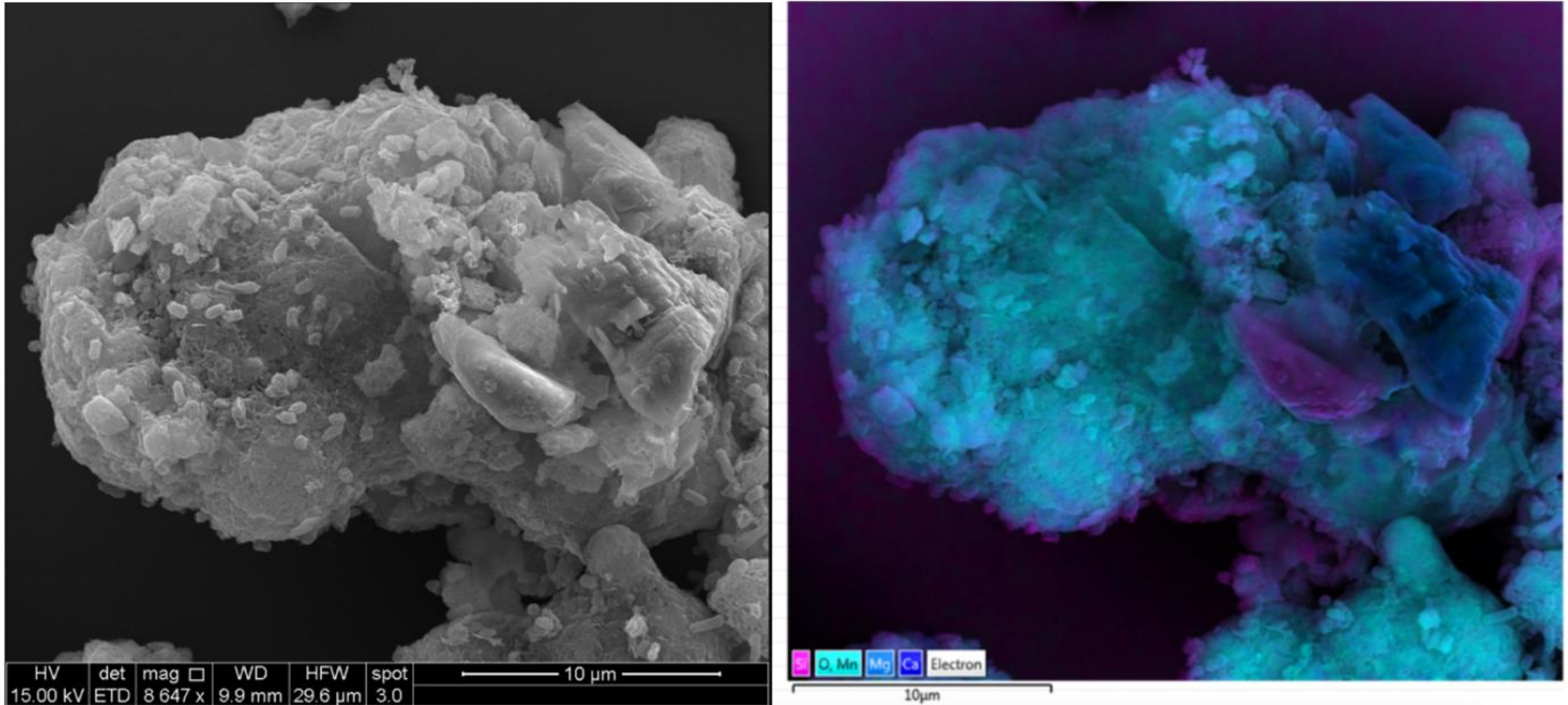


Solubilization of REEs from AMD Solids with Bacterial Isolates





SEM of KB7 with Glasgow AMD Solids



Mn oxides from Glasgow AMD covered in rod shaped bacteria KB7
consistent with these isolates being *Bacillus* sp.

KB7 & JR07 are the stronger solubilizers of AMD solids (REEs)

Isolate	16S <i>rrn</i> Identity	Biofilm	Lactic Acid
AV20	90% <i>Bacillus cereus</i>	-	-
AV21	98% <i>Corynebacterium sp.</i>	-	-
AV22	83% <i>Bacillus sp.</i>	-	-
AV24	98% <i>Corynebacterium sp.</i>	-	-
KB7	100% <i>Bacillus pseudomycoides</i>	+	+
JR07	100% <i>Bacillus mycoides</i>	+	+

Both isolates

Direct interactions with AMD solids (SEM)

Form Biofilms

Produce Lactic Acid



Characterize AMD Solids

Chemical Composition
ICP-MS/OES

Microbial AMD
Solid REE Solubilization

Metal Release from AMD Solids
FAD, ICP-MS/OES

Characterize AMD REE Release
Interaction with Solids, Acidogenesis

La Oxide Acidogenic Release
Colorimetric Assay UV-Vis

Selective Bacterial
Biomining of La

Colorimetric Assay
UV-Vis

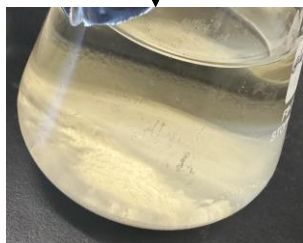


Acidogenesis Isolates KB7 & JR07

↑ Soluble La(III) from LaOx



KB7
JR07
Sterile



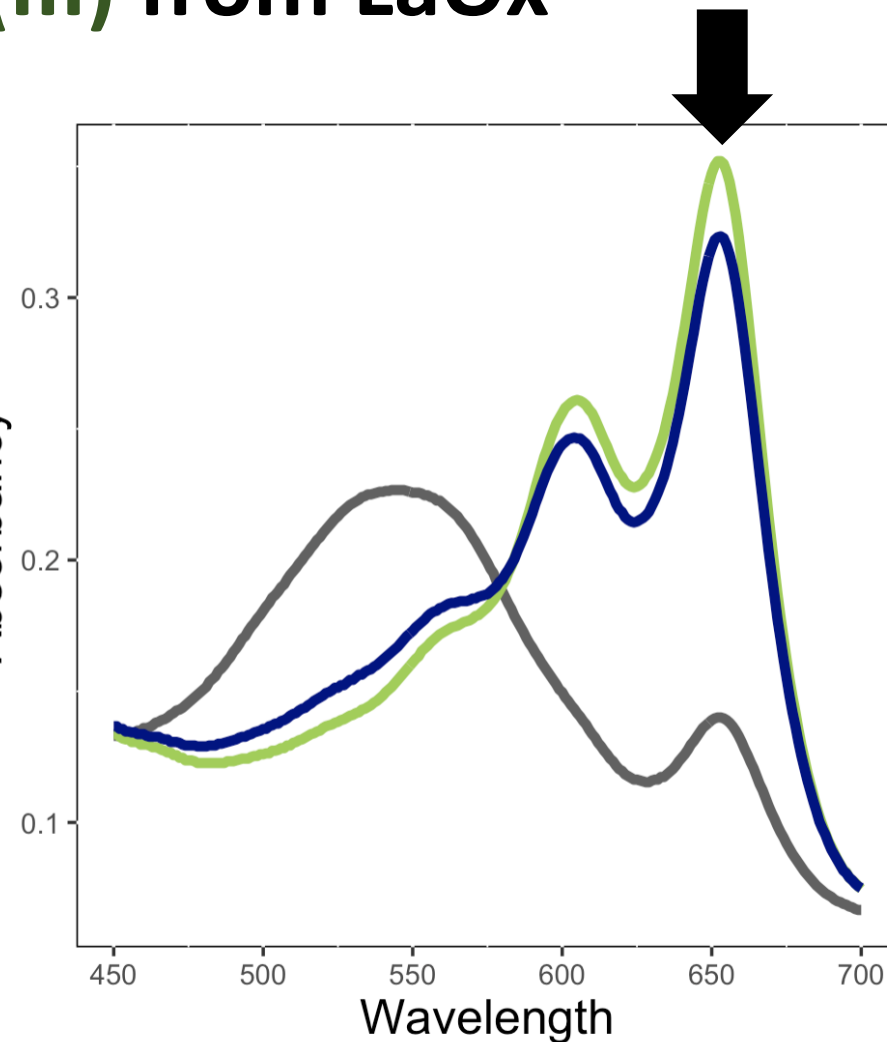
n = 3
Incubate 30°C

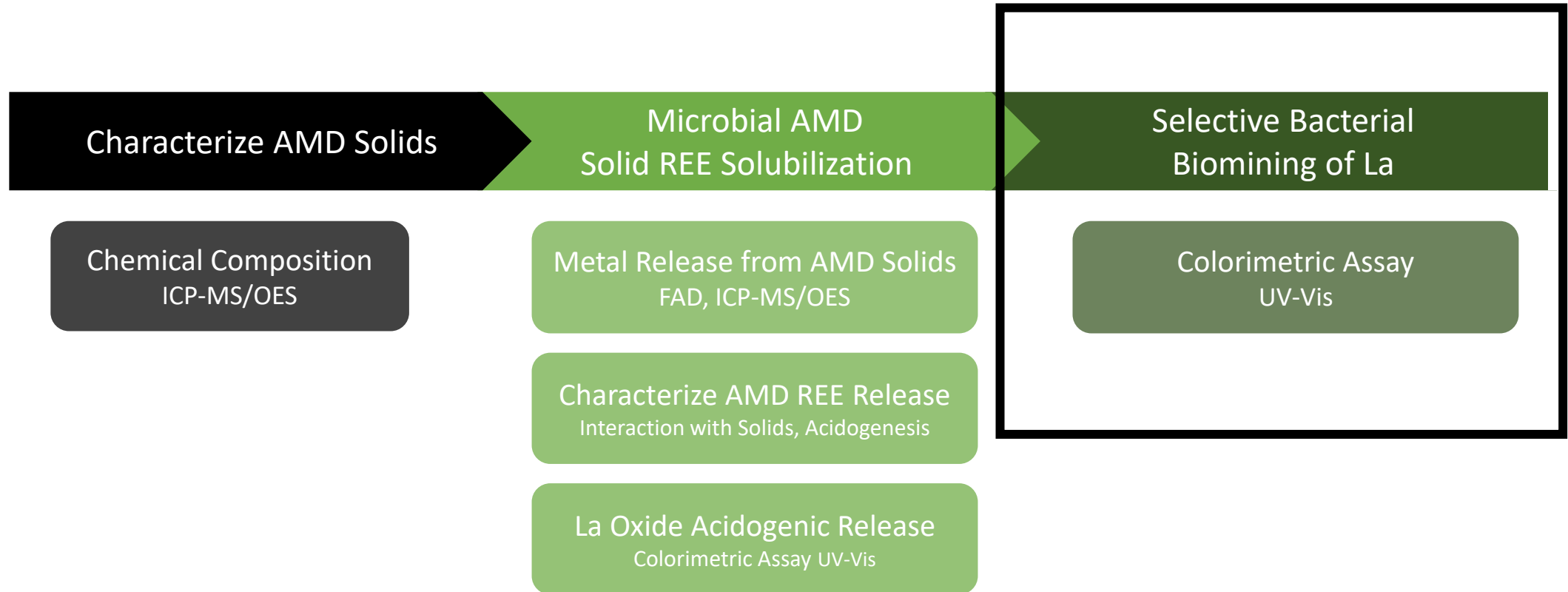


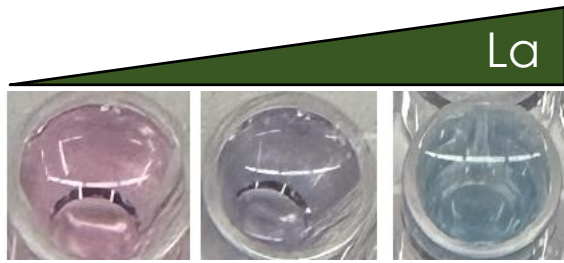
La

Day 0 Day 1 Day 2 Day 3

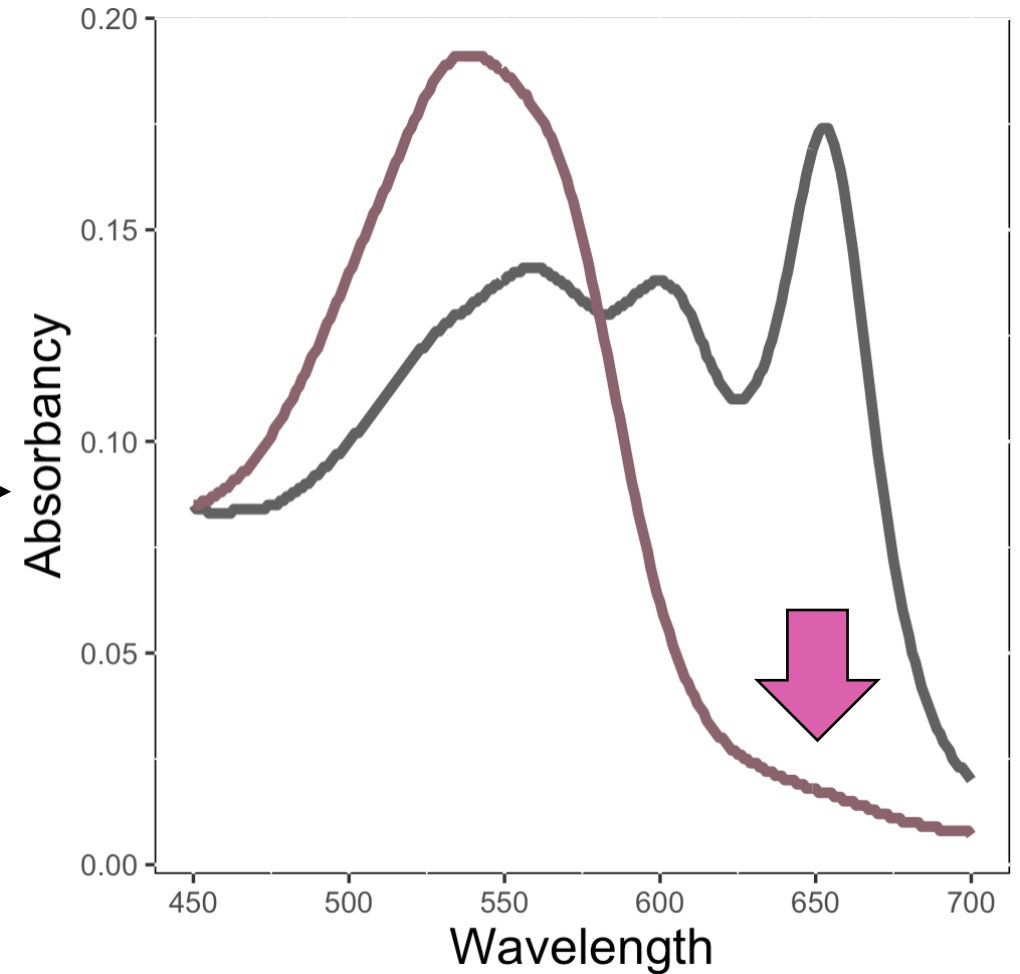
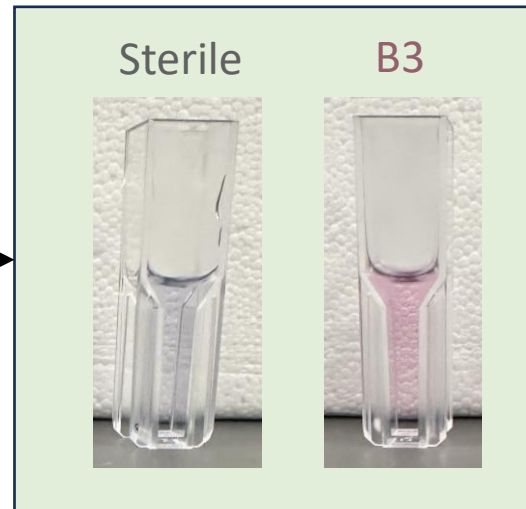
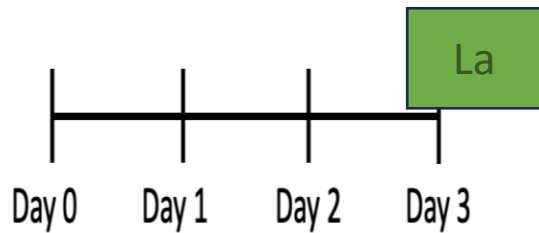
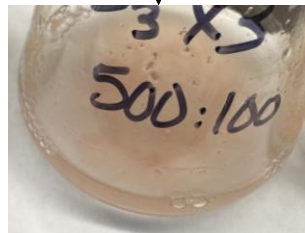
Absorbance



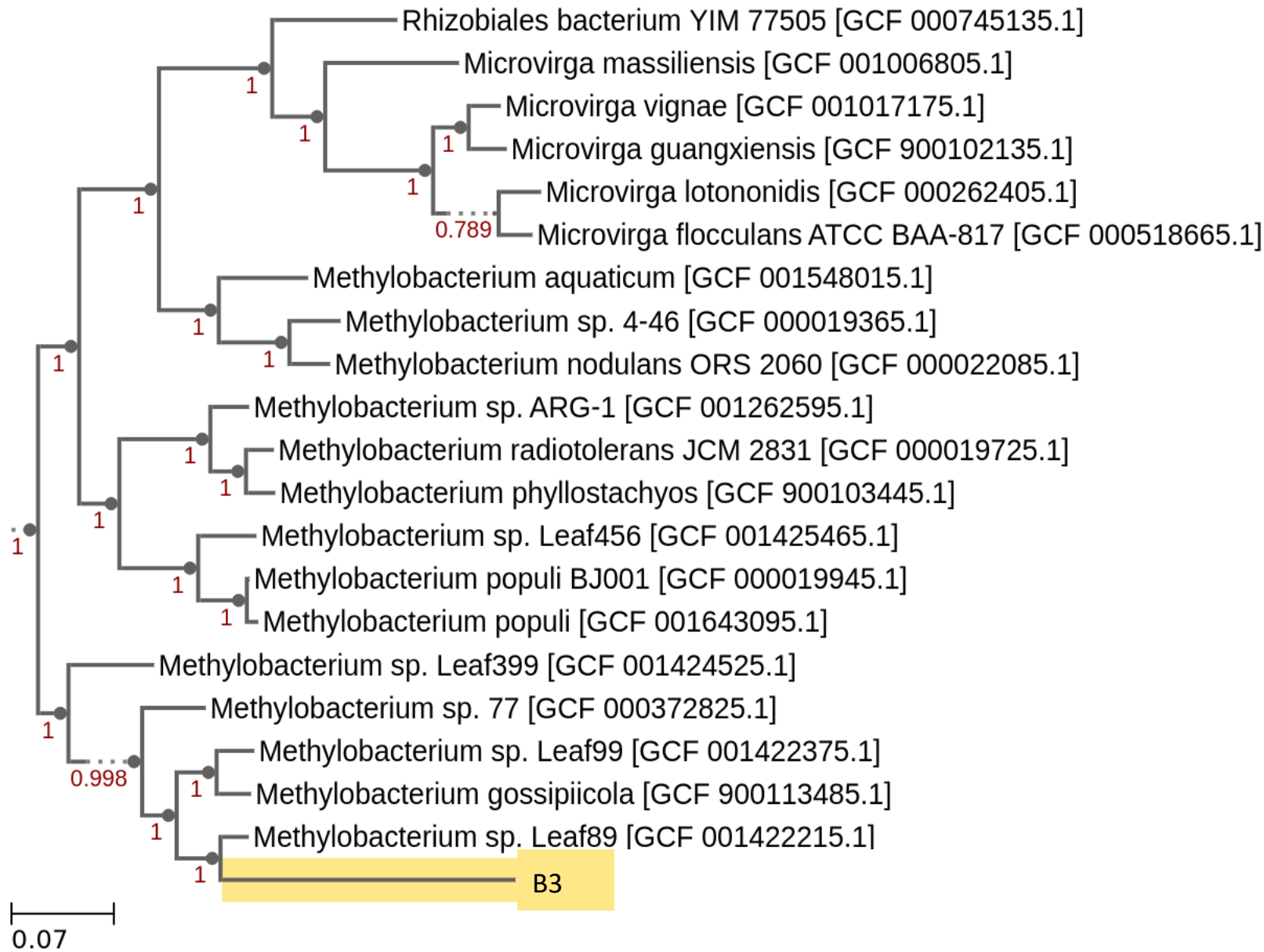




Decrease in Soluble **La(III)** when Bacterial Isolate **B3** is Present



Characterizing B3



Future Directions

Publish / Patent Work

Scale-up Biomining Process for In-Field Applications

Thank You!!

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I'm looking for opportunities post-doctorate.

Let's connect!

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CV



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