Microbial Biomining for the Release and Recovery of Rare Earth Elements in Abandoned Coal Mine Drainage

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Background Information

Abandoned Coal-Mine Drainage (AMD)

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

Acidogenic Manganese Solubilization

Abandoned Mine Drainage (AMD)

Coal Mining in Pennsylvania

Unregulated 1700s → 1945

Legacy mines ~11,000 mines

https://wvhistoryonview.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

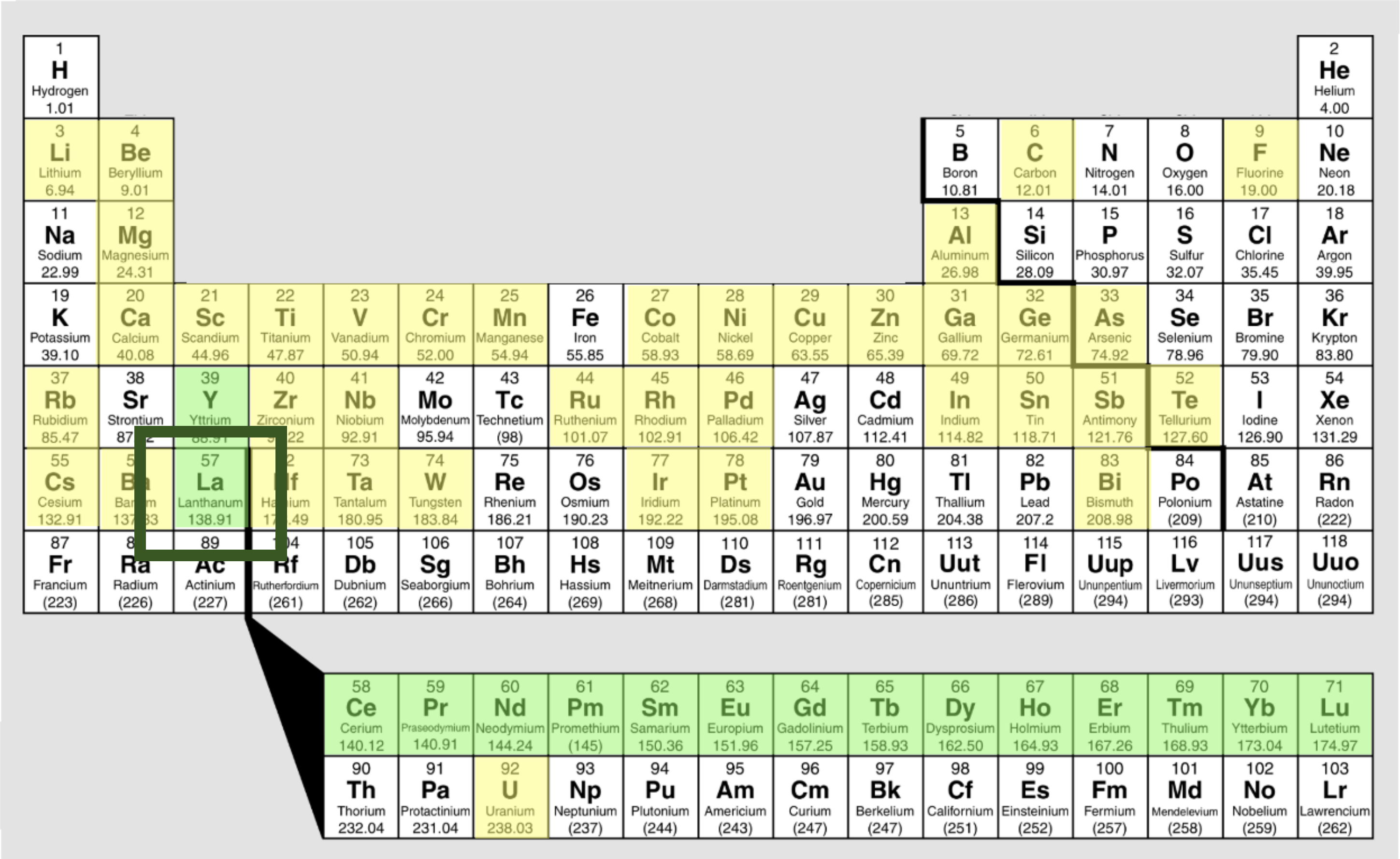
Conventional REE Extraction

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)



Acidogenic Bacteria Solubilize Mn

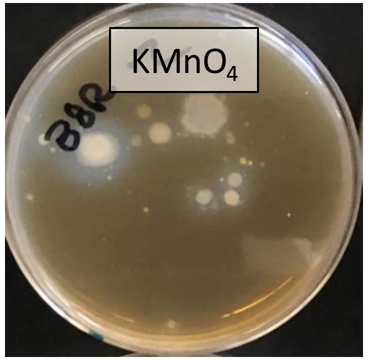
Isolate	16S rRNA Identity
AV20	90% *Bacillus cereus*
AV21	98% *Corynebacterium sp.*[▽]
AV22	83% *Bacillus sp.*
AV24	*98% Corynebacterium sp.*
KB7	100% *Bacillus pseudomycoides*[▽]
JR07	100% *Bacillus mycoides*[▽]
Sterile	NA

[▽]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

Kayla Brennan, Josh Robinson

Acidogenic Bacteria Solubilize Mn

Isolate	16S rRNA Identity	Reduces $KMnO_4$*
AV20	90% *Bacillus cereus*	+
AV21	98% *Corynebacterium sp.*▽	+
AV22	83% *Bacillus sp.*	+
AV24	*98% Corynebacterium sp.*	+
KB7	100% *Bacillus pseudomycoides*▽	+
JR07	100% *Bacillus mycoides*▽	+
Sterile	NA	-



▽Whole genome sequencing (WGS)

*Differential Manganese Reduction Media $KMnO_4$

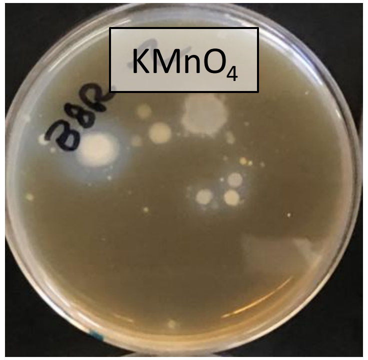
+Differential Manganese Reduction Media MnO_2

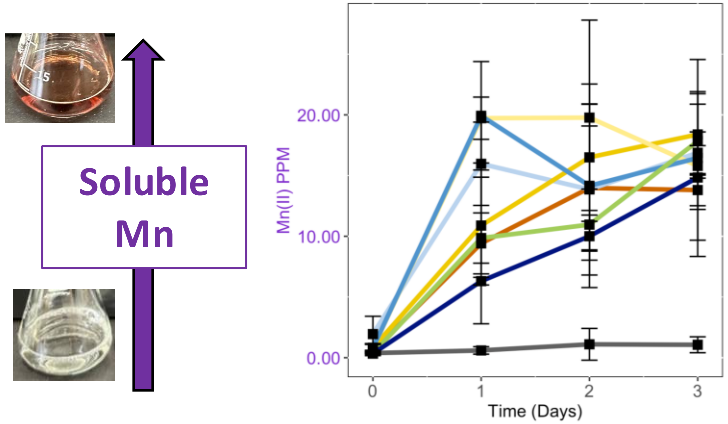
✦Acid Production Determined by Phenol Red/pH probe/TSI Slants

NA = Not applicable

Acidogenic Bacteria Solubilize Mn

Isolate	16S rRNA Identity	Reduces $KMnO_4$*	Reduces MnO_2+
AV20	90% *Bacillus cereus*	+	+
AV21	98% *Corynebacterium sp.*▽	+	+
AV22	83% *Bacillus sp.*	+	+
AV24	98% *Corynebacterium sp.*	+	+
KB7	100% *Bacillus pseudomycoides*▽	+	+
JR07	100% *Bacillus mycoides*▽	+	+
Sterile	NA	-	-





▽Whole genome sequencing (WGS)
*Differential Manganese Reduction Media $KMnO_4$
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NA = Not applicable

Kayla Brennan, Josh Robinson

Acidogenic Bacteria Solubilize Mn

Isolate	16S rRNA Identity	Reduces $KMnO_4$*	Reduces MnO_2+	Produces Acid✦
AV20	90% *Bacillus cereus*	+	+	+
AV21	98% *Corynebacterium sp.*▽	+	+	+
AV22	83% *Bacillus sp.*	+	+	+
AV24	98% *Corynebacterium sp.*	+	+	+
KB7	100% *Bacillus pseudomycoides*▽	+	+	+
JR07	100% *Bacillus mycoides*▽	+	+	+
Sterile	NA	-	-	-

▽Whole genome sequencing (WGS)
*Differential Manganese Reduction Media $KMnO_4$
+Differential Manganese Reduction Media MnO_2
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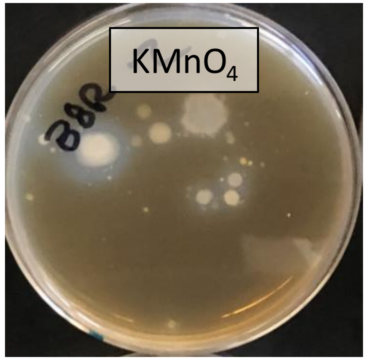

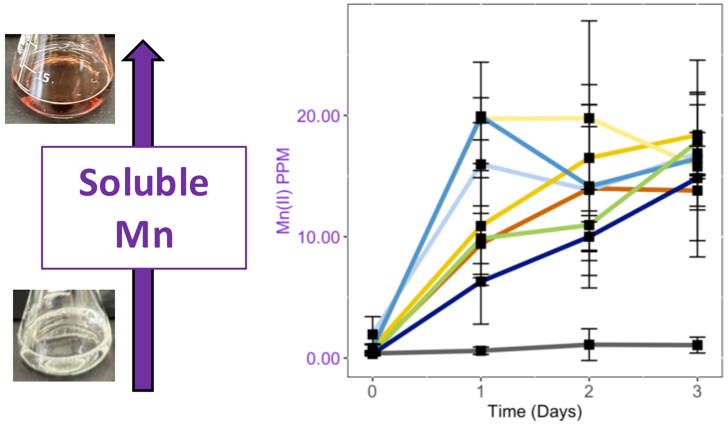

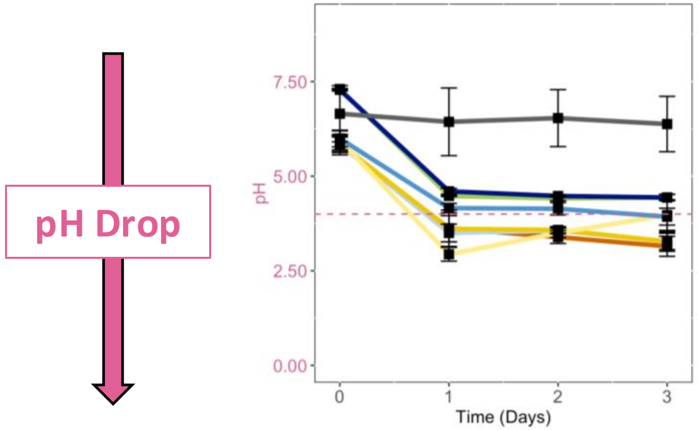

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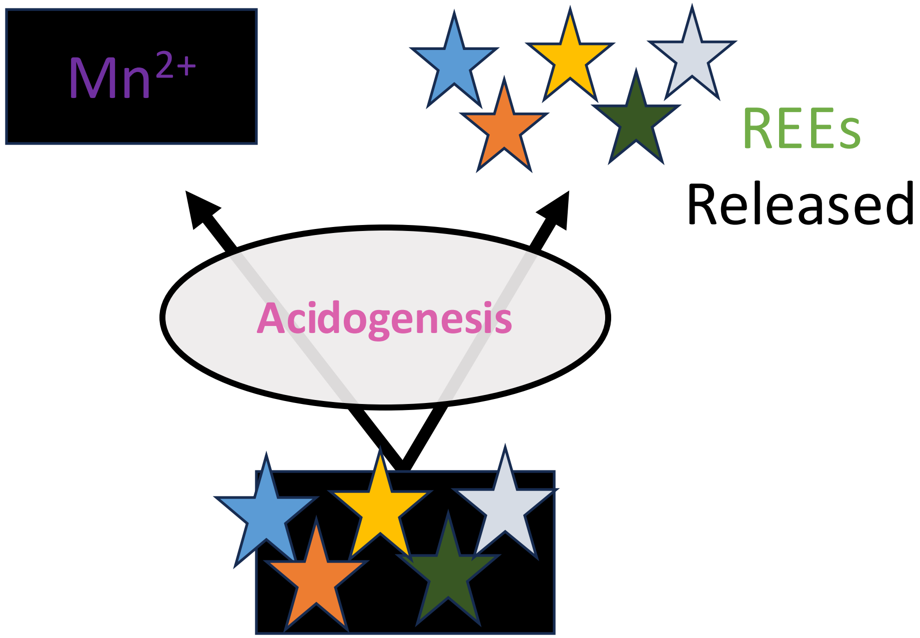
Can Acidogenic Bacteria Biomine Co-Precipitated REEs in AMD Solids?

Low Temps

No Expensive/Aggressive Reagents

Extraction Efficiency >80%

REE Bioleaching Understudied & Poorly Understood



AMD Solids (MnOx)
REEs Co-Precipitated

Fathollahzadah 2018

Biomining
Acidogenic Release of REEs & La Recovery

Characterize AMD Solids

- Chemical Composition
  ICP-MS/OES

Microbial AMD Solid REE Solubilization

- Metal Release from AMD Solids
  ICP-MS/OES
- Characterize AMD REE Release
  Interaction with Solids, Acidogenesis

Selective Bacterial Biomining of La

- Colorimetric Assay
  UV-Vis

AMD Systems to Target for Biomining

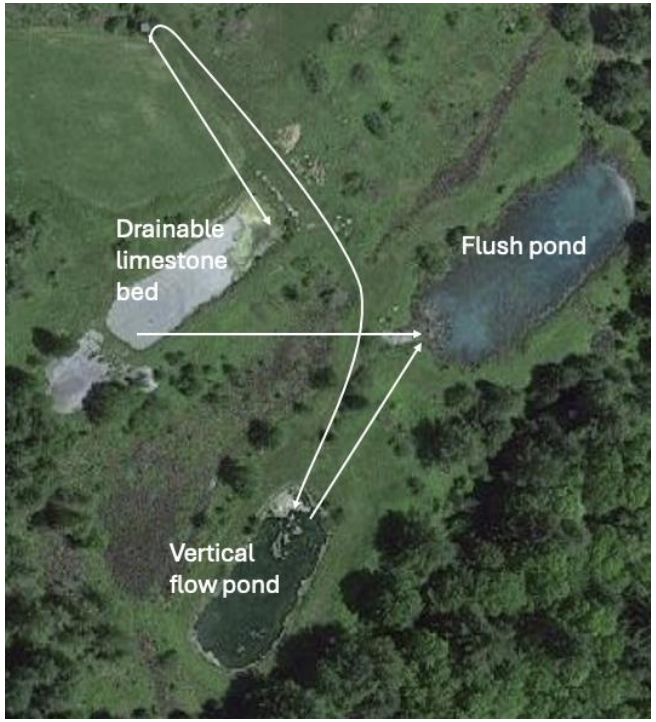
Recommended by NETL based on previous work by Ben Hedin, PhD

Wingfield Pines

Sterrett

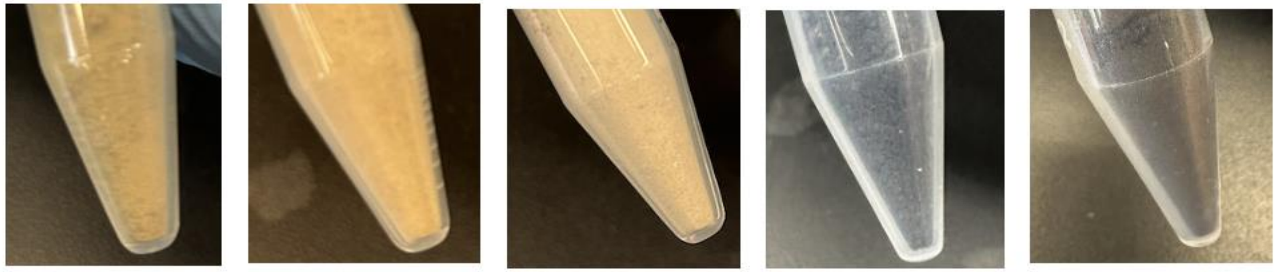
Kentucky Hollow

Scootac



Glasgow

Chemical Compositions of AMD Solids



Wingfield Pines | Sterrett | Kentucky Hollow | Scootac | Glasgow

REEs

	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   <DL 0

Colleen Hoffman, PhD, Sam Flett, Sierra McDermott, PAL

Biomining
Acidogenic Release of REEs & La Recovery

Characterize AMD Solids

Microbial AMD
Solid REE Solubilization

Selective Bacterial
Biomining of La

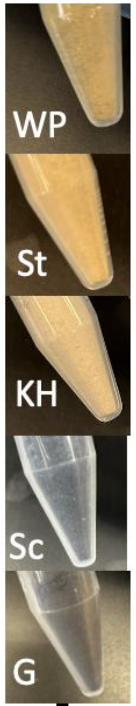
Chemical Composition
ICP-MS/OES

Metal Release from AMD Solids
ICP-MS/OES

Colorimetric Assay
UV-Vis

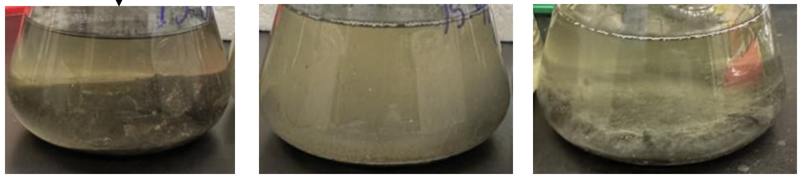
Characterize AMD REE Release
Interaction with Solids, Acidogenesis

Solubilization of REEs from AMD Solids with Bacterial Isolates

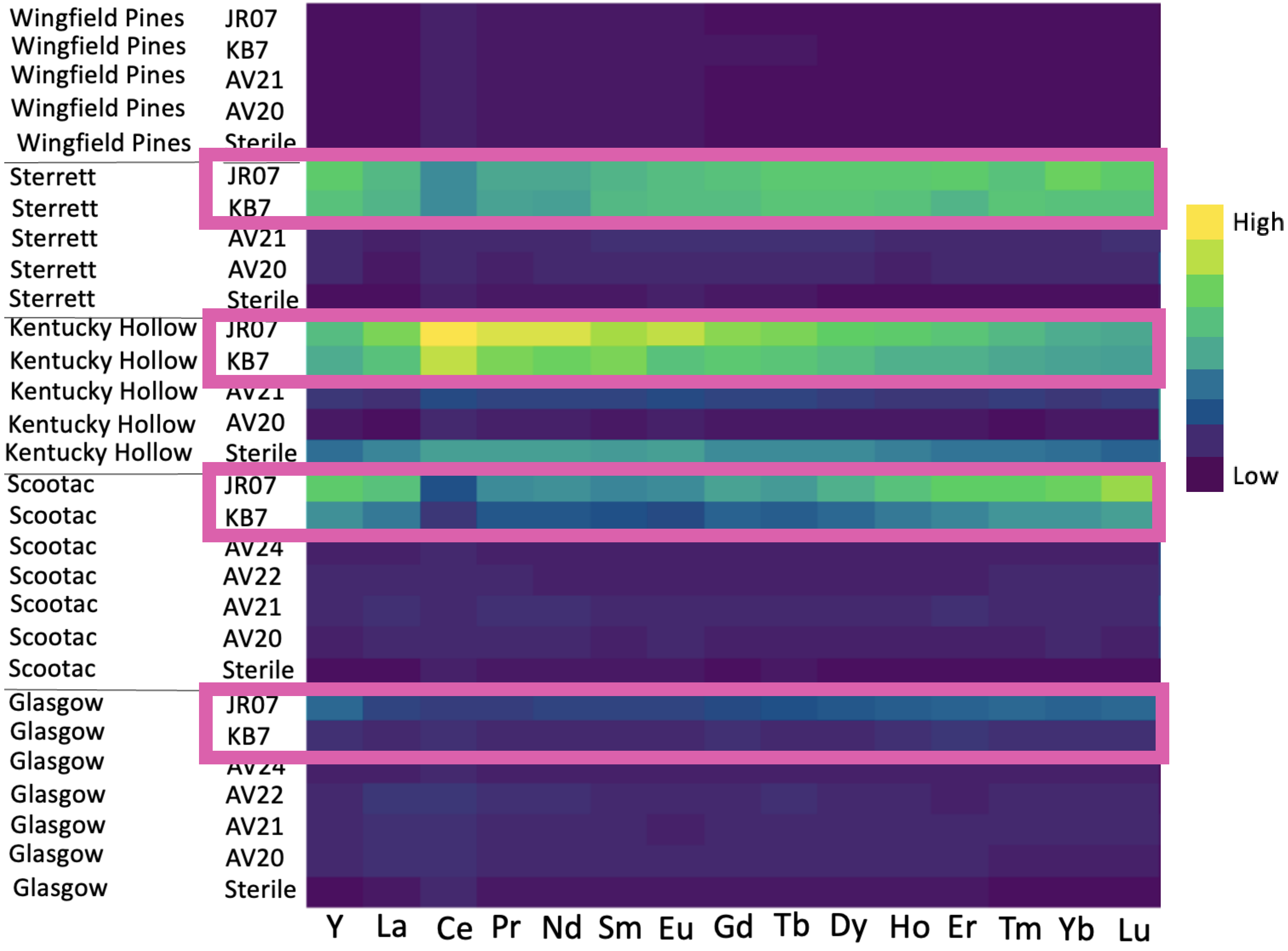


	Total REEs		
	Sc	KH	St
AV20			
AV21			
AV22			
AV24			
KB7	18%	49%	28%
JR07	34%	58%	29%
Sterile			

KB7 & JR07 best
@ ↑soluble REEs



Sterile AV20 KB7

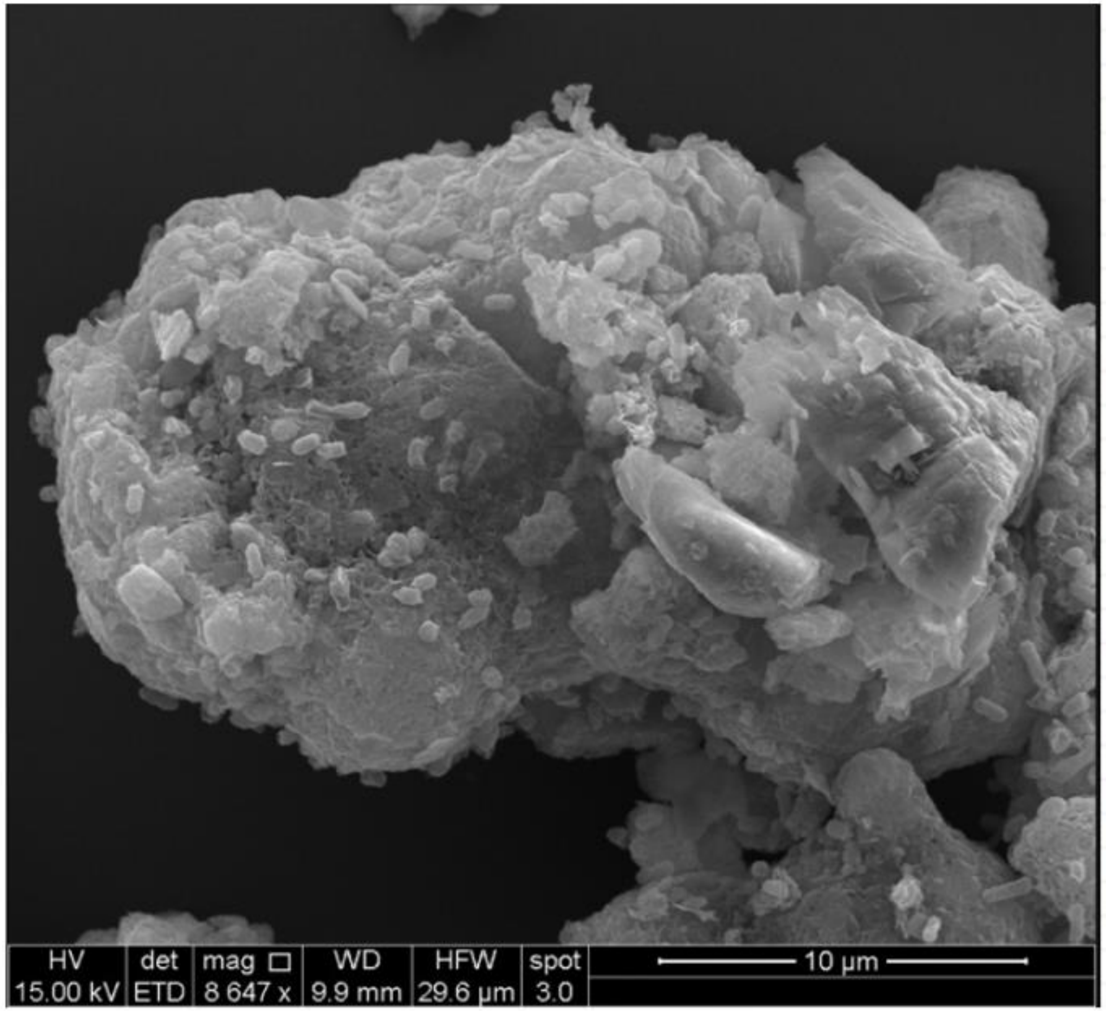


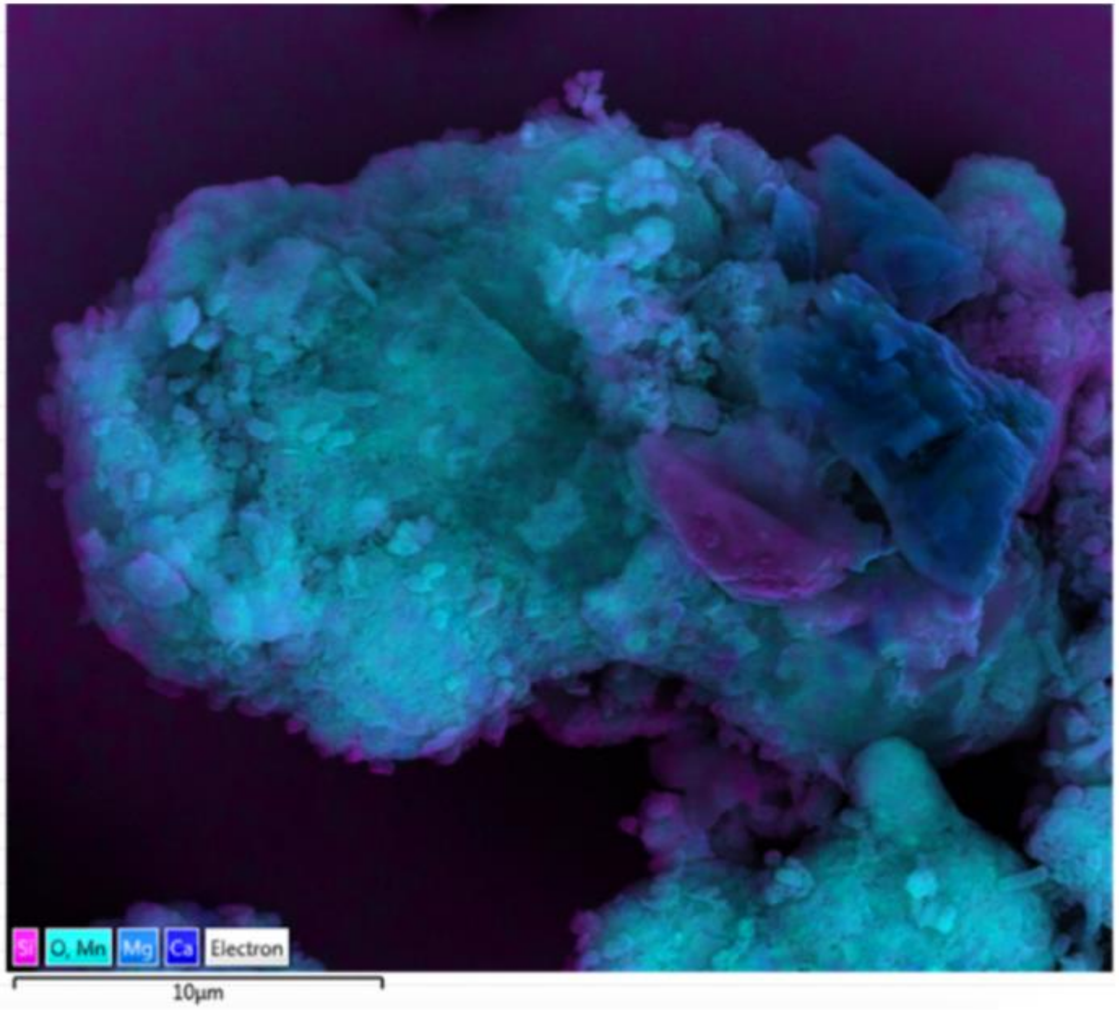
Sam Flett, Sierra McDermott, & PAL

Biomining
Acidogenic Release of REEs & La Recovery

Characterize AMD Solids	Microbial AMD Solid REE Solubilization	Selective Bacterial Biomining of La
Chemical Composition ICP-MS/OES	Metal Release from AMD Solids ICP-MS/OES	Colorimetric Assay UV-Vis
	Characterize AMD REE Release Interaction with Solids, Acidogenesis	

SEM Shows Direct Interaction of KB7 with Mn in Glasgow AMD Solids





Mn oxides from Glasgow AMD covered in rod shaped bacteria

Consistent with these isolates being *Bacillus sp.*

Meghan Beebe

KB7 & JR07 Produce Lactic Acid and Biofilms Potentially Key for REEs Release from AMD Solids

Isolate	16S rRNA Identity	Biofilm	Lactic Acid
AV20	90% *Bacillus cereus*	-	-
AV21	98% *Corynebacterium sp.*	-	-
AV22	83% *Bacillus sp.*	-	-
AV24	98% *Corynebacterium sp.*	-	-
KB7	**100% *Bacillus pseudomycoides***	**+**	**+**
JR07	**100% *Bacillus mycoides***	**+**	**+**

Can Bacteria Selectively Recover La from Solution?

Aerobic Methylotrophic Bacteria Have Proteins that are specific for Lanthanum

Mattocks 2023, Ye 2023
Xie 2023, Good 2021

Biomining

Acidogenic Release of REEs & La Recovery

Characterize AMD Solids → Microbial AMD Solid REE Solubilization → Selective Bacterial Biomining of La

Characterize AMD Solids
- Chemical Composition
  ICP-MS/OES

Microbial AMD Solid REE Solubilization
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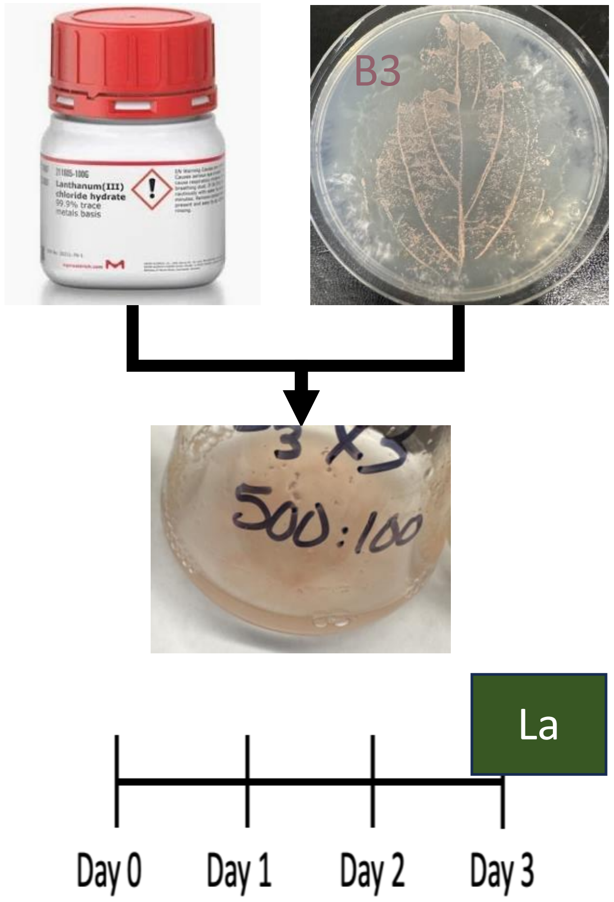
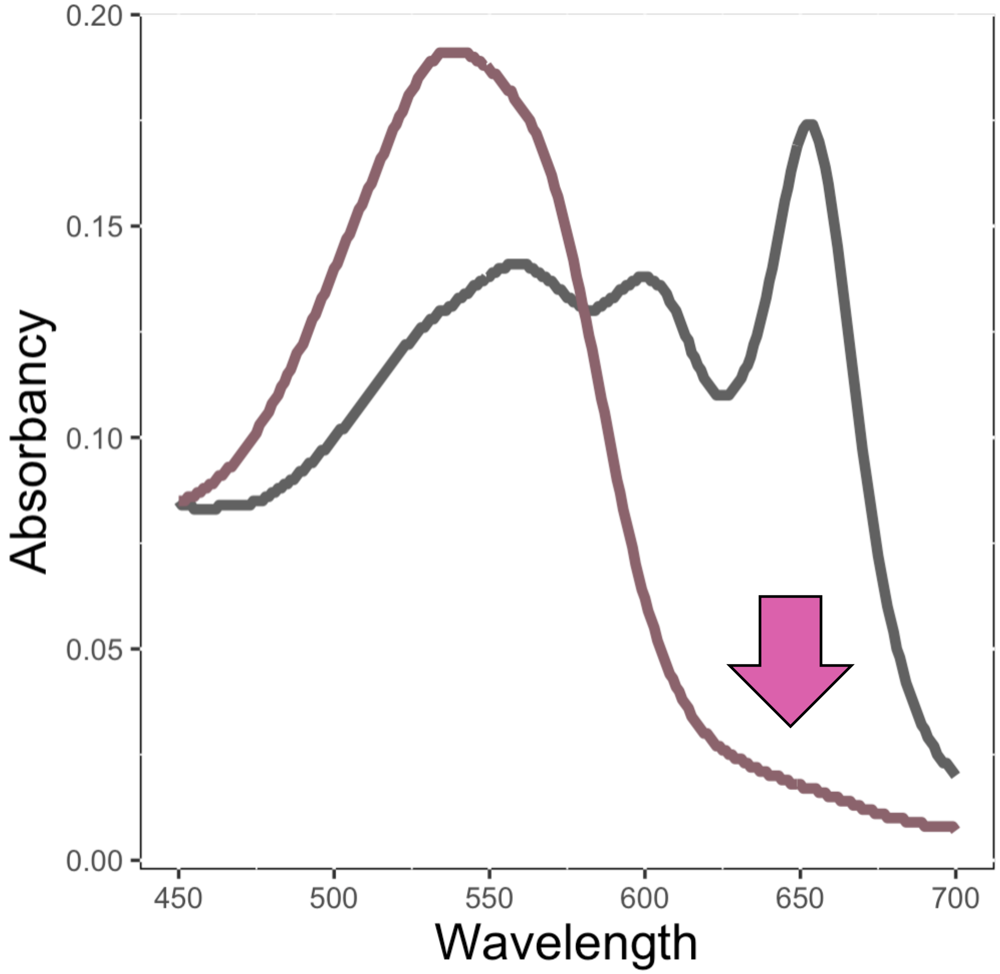
Selective Bacterial Biomining of La
- Colorimetric Assay
  UV-Vis

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



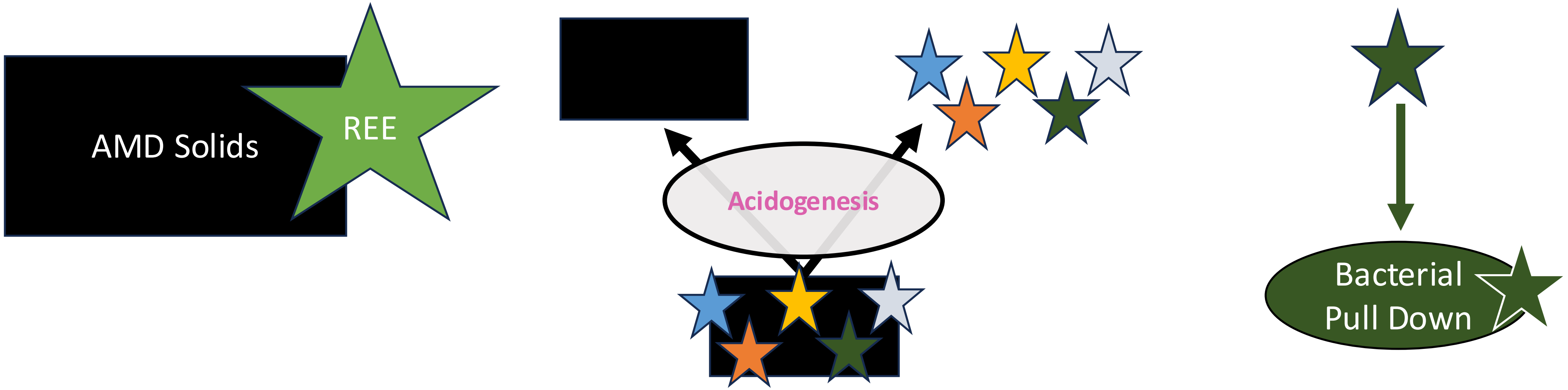


Bethann Wilson, PhD, Cassandra Ziegler

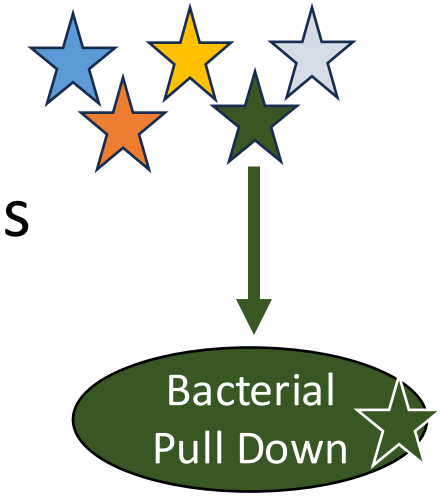
Hogendoorn 2018, Martinez-Gomez 2015

Biomining: Bacteria Can Release REEs from AMD Solids by Acidogenesis and Recover La

Characterize AMD Solids	Microbial AMD Solid REE Solubilization	Selective Bacterial Biomining of La
AMD systems are rich in REEs	Acidogenesis bacterial isolates solubilize REEs from AMD solids	Bacteria can recover La from solution



Future Directions



Recover La from REEs Released from AMD Solids

Characterize B3

Identify Enzyme in La Sequestration

Scale-up Biomining Process for In-Field Applications

Publish / Patent Work

Thank You!!

NETL

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