Biomining: An Opportunity for U.S. Critical Mineral Independence

Cornell Brooks Tech Policy Institute
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Executive summary

Biomining, defined as the use of microorganisms to extract metals from ores and waste streams, is an emerging but increasingly strategic technology in the global minerals sector. The market was estimated to be ~$2 billion in 2024, led by industrial operations in Chile and Finland. While adoption is growing, biomining remains niche compared to conventional methods. The market is anticipated to grow as the technology is applied to new minerals and the demand for critical minerals, such as rare earth elements, rises

The U.S. can be described an innovation hub for biomining; while commercial operations at scale do not yet exist, the U.S. is home to multiple startups and is strong in biotech R&D. While the federal government has invested some money into biomining, the amounts remain small compared to more conventional minerals extraction and processing.

The small relative market size, limited policy support, and faster-moving global competitors are the primary barriers to growing biomining in the U.S. Due to market dynamics, the U.S. government must invest in biomining to unlock private capital, expand R&D efforts, and grow a sector that has the potential to increase U.S. mineral independence

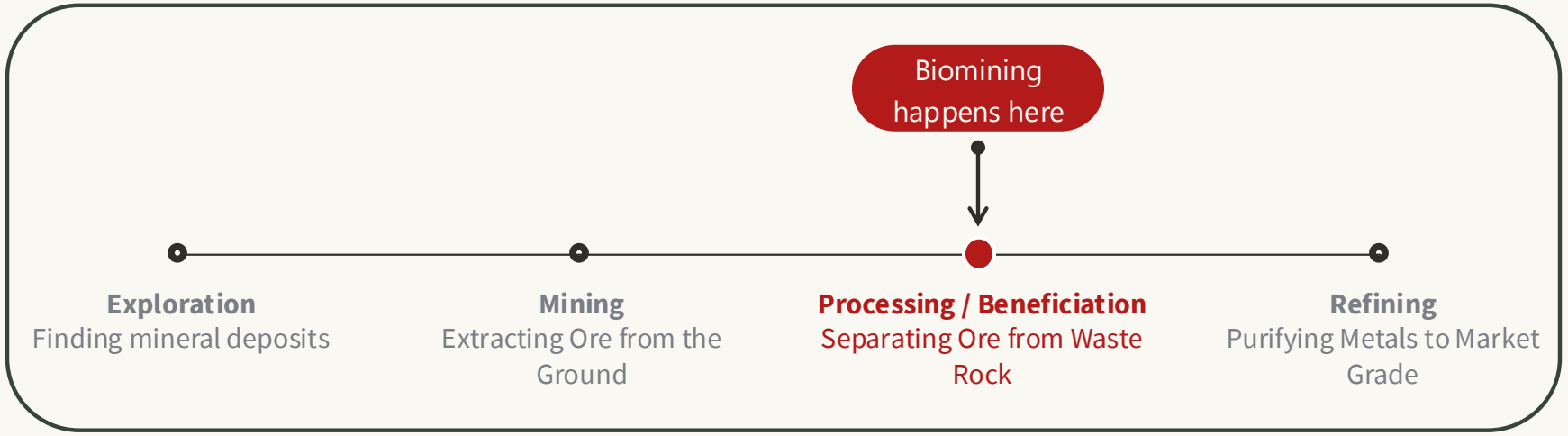
INTRODUCTION

Executive Summary, a Brief Overview on Biomining, and the Critical Mineral Challenge

What is biomining?

Biomining uses **specialized bacteria** and other microorganisms that naturally thrive in **extreme environments** to extract valuable metals from ore

Despite the name, it doesn't involve traditional "mining" techniques like drilling or blasting. Instead, it typically happens **after ore has been extracted** from the ground, where it serves as a **cleaner alternative** to chemical processing



What is biomining?

Biohydrometallurgy
Biohydrometallurgy is the broader scientific field that uses microorganisms in metallurgy to extract metals from ores and other materials. It includes biomining, bioremediation, and other biological metals processes

Biomining
Biomining is the subset of biohydrometallurgy focused on extracting metals from ores. The term is sometimes used interchangeably with bioleaching

Two Main Mechanisms:

Direct
Bacteria physically attach to minerals and break them down

Indirect:
Bacteria create chemicals (acids/oxidants) that dissolve minerals

Two Main Applications

Bioleaching
Extracts target metals directly, primarily copper, nickel, zinc, cobalt, and uranium

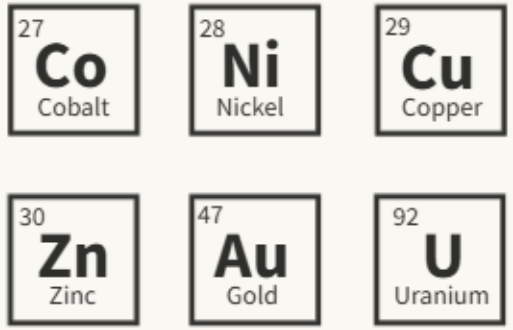
Biooxidation
Removes barrier minerals to access valuable metals, mainly used for gold extraction

How does biomining work?

Microorganisms and Their Function

Specialized bacteria extract metals by breaking down sulfide minerals, creating acidic conditions, and oxidizing metals for extraction. These microorganisms thrive in extreme environments where traditional methods would fail.

Common Metals Recovered



Fact:
Between 10-15% of the world's copper comes from bioleaching

Biomining Methods

1. **Heap Leaching:** Bacterial solutions are sprayed over ore piles to slowly extract metals over months or years.
2. **Tank Leaching:** Ore and bacteria are mixed in controlled reactors for rapid metal extraction.
3. **Dump Leaching:** Mine waste piles are treated with bacteria to recover residual metals.
4. **In-situ Leaching:** Bacterial solutions dissolve metals underground, which are then pumped to the surface.

The biomining process has advantages – but a few drawbacks as well

Energy Savings

By operating at ambient temperatures instead of high-heat smelting, biomining slashes energy consumption. For copper production specifically, energy use drops 87% - from 6,000 kWh/ton in conventional smelting to just 725 kWh/ton with bioleaching.

Emissions Reduction

The elimination of energy-intensive smelting translates directly to lower carbon footprints. Copper biomining cuts CO2 emissions by approximately 50%, while some operations achieve even better results - Terrafame's nickel bioleaching delivers 60-68% lower emissions compared to conventional processing.

Superior Metal Recovery

Biomining excels at extracting metals from challenging ores. While conventional methods recover only 60-65% from low-grade copper ores, bioleaching achieves 90-95% recovery rates. This efficiency extends to many other metals.

Increased Risk of Acid Mine Drainage (AMD)

Biomining actively cultivates acid-producing bacteria that generate sulfuric acid at pH 1.5-3 throughout operations. Unlike conventional mining where AMD is an unwanted byproduct, biomining depends on maintaining acidic, metal-rich solutions for up to months of processing. Millions of liters of acidic solution continuously percolate through massive ore piles - all dependent on liner integrity to prevent groundwater contamination.

Early Operational Failures

The 2012 Talvivaara disaster remains biomining's most severe failure. When the gypsum pond leaked, 1.2 million m^3 of contaminated water escaped, with 240,000 m^3 flowing beyond mine boundaries. Uranium levels reached 3.5x legal limits, prompting Finland's Environment Minister to label it "a serious environmental crime." The disaster led to bankruptcy in 2014, criminal charges against executives, and lasting contamination of multiple lakes, demonstrating the catastrophic potential when bioheap containment fails.

Sources: Hoque, M.E. & Philip, J. Obbard, "Biotechnological recovery of heavy metals from secondary sources—An overview," (2011); Roberto, Francisco F. & Axel Schippers, "Progress in bioleaching: part B, applications of microbial processes by the minerals industries," PMC (2022), PMCID: PMC9424069; Tezyapar Kara, I., K. Kremser, & F. Coulon, "Bioleaching metal-bearing wastes and by-products for resource recovery: a review," Environmental Chemistry Letters, Volume 21 (2023); Thunder Said Energy, "Heap Leaching: Energy Economics" and "Bioleaching Case Studies and Examples" (2024); Terrafame Media Release, "Terrafame's nickel sulphate production offers the lowest carbon footprint in the industry" (2023); MIT Course Materials, "Bioleaching" (2015); Springer, "A comprehensive review on sustainable utilization and management of mining waste and tailings for circular economy" (2023); American Geosciences Institute, "What is biomining?" Professional FAQ; Safety Investigation Authority of Finland, "Environmental accident at Talvivaara" Investigation Report Y2012-03 (2013); Wikipedia, "Ahtium" entry.

Biomining has traditionally been used with commodity metals, but use in critical minerals has been expanding

While biomining is most established for larger commodities like copper and gold, it's increasingly being applied to **critical minerals** — materials essential to U.S. economic and national security with vulnerable supply chains

Nickel, cobalt, and zinc are all U.S. critical minerals currently being biomined. Finland's Terrafame facility — the world's only economic cobalt biomining operation — produces 1.2% of global nickel, <1% of global cobalt, and 0.4% of global zinc*

As supply chains become increasingly important to national security, biomining offers a sustainable domestic alternative for critical mineral production

Key initiatives advancing critical mineral biomining include: **DARPA EMBER Program** (REE, $4.6M funding), **Lawrence Livermore National Laboratory** (REE research), **Cemvita Factory** (lithium biomining), and **BioMetallica** (REE bioleaching)

*The Kasese facility in Uganda previously biomined cobalt but ceased operations in 2013

The primary challenge for U.S. critical mineral access is processing – biomining may provide a solution

While the U.S. and allies have access to mineral deposits, China controls over 90% of global processing capacity for critical minerals — creating a dangerous vulnerability in our supply chains

This processing monopoly is no accident: China has invested **$13.8B+ annually** to maintain control through massive state subsidies, minimal environmental standards, and strategic price manipulation that drives competitors out of business

Traditional processing methods require massive capital investment and face strict environmental regulations in Western countries, making it nearly impossible to compete with China's subsidized operations

Biomining offers a strategic alternative by providing cleaner, more cost-effective processing methods that could help Western nations rebuild domestic processing capacity without compromising environmental standards.

However, biomining has opportunities and challenges to face in order to scale operations

Opportunities

Processing Independence. Biomining offers a strategic alternative by providing cleaner, more cost-effective processing methods that could help Western nations rebuild domestic processing capacity without compromising environmental standards, critical as China controls 80 to 90% of global processing capacity.

Environmental Advantages. The process takes place at atmospheric pressure and lower temperatures than smelting, reducing energy consumption at the mining site. Additionally, modular deployment can allow distributed processing closer to mining sites, reducing transportation costs and emissions.

Economic Returns on Low-Grade Resources. Capital expenditure for bioleaching operations is approximately 50% lower than conventional smelting/refining operations, while enabling processing of ores containing only .5-1% copper, below the economic threshold for conventional refining.

Challenges

Long Development Timelines. Bioprocessing in tanks generally takes a long time to process

Limited Industrial Maturity Despite Decades of Development. The mining sector has long been regarded as having a conservative culture, which is resistant to change, with structural barriers to innovation, such as high capital intensity and mining firms were put off from developing these technologies because of the large development timescale (typically more than 20 years)

Historical Environmental Setbacks. The 2012 Talvivaara facility released 1.2 million m^3 of metal-contaminated water despite being considered state-of-the-art, demonstrating ongoing challenges in containing acid mine drainage. Biomining wastewater management has thus far not operated as originally planned at multiple facilities, requiring continuous monitoring and intervention.

CURRENT STATE & MARKET

Overview of the current state of the global biomining market

Biomining is an emerging sector valued at ~$1.8B in 2024

The global biomining market is currently valued at **approximately $1.8 billion in 2024**, with **market growth projected at a modest 3.7% CAGR, reaching approximately $2.4 billion by 2032**. **Chile leads global adoption**, contributing roughly 10% of the country's copper production through biomining operations, while **Finland operates one of Europe's largest biomining facilities**. The **bioleaching segment represents the most established commercial application**, with emerging growth in **battery metals processing**

The technology is primarily applied to **copper (15-20% of global production) and gold processing (about 5% via bio-oxidation)**. Biomining is increasingly being deployed for **battery metals like nickel and cobalt**, offering **significantly lower carbon footprints compared to traditional extraction methods**. The sector is also expanding into **strategic metals processing**, including rare earth elements and lithium recovery from low-grade ores, mine waste, and electronic scrap

However, **the industry faces significant headwinds that temper growth expectations**. **Key industry leaders like Chile are experiencing declining biomining applications** as ore grades decrease and companies transition to alternative extraction methods. **The depletion of ideal ore bodies suitable for biomining**, combined with competing technologies, has led to a cautious industry outlook. **It represents a niche technology rather than a transformative force in global mining**

Sources: Credence Research, "Bioleaching Market Size, Growth, Share and Forecast 2032" (November 2024); Terrafame company reports; Kitco News, "Finnish nickel producer Terrafame to start uranium recovery in 2024" (December 2022); Brierley & Brierley, "Progress in bioleaching: applications of microbial processes by the minerals industries," PMC (2022); Vera et al., "Copper Bioleaching Operations in Chile: Towards New Challenges and Developments," Springer (2023); Innovations in Copper, copper.org; LLNL Science & Technology Review (April 2024).

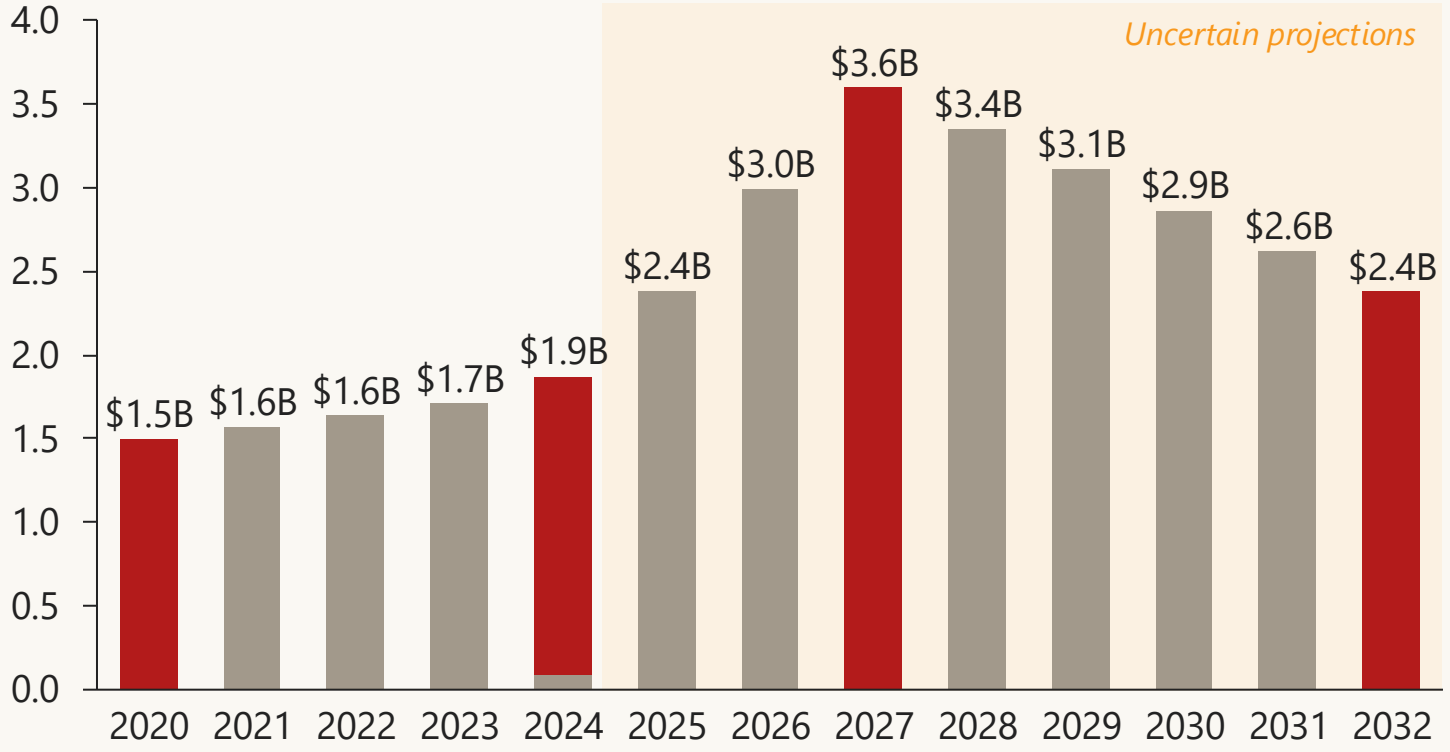
Biomining is an emerging sector with uncertain growth

Estimates of the 2024 biomining market size cluster between **$1.8B-$1.9B,** indicating that biomining is current a niche market relative to other mining sectors

Some estimates project that the market will reach $3.6B in 2027, while other projects size the market at ~$2.4B in 2032

Given that growth projections conflict, it suggests that there is **uncertainty and limited reliability** of the future market size

Estimated biomining market size ($ billion)



Sources: Credence Research. "Biomining Market: Global Industry Size, Share & Forecast 2027." November 16, 2023. https://www.credenceresearch.com/report/biomining-market; Credence Research. "Bioleaching Market Size, Growth, Share and Forecast 2032." November 15, 2024. https://www.credenceresearch.com/report/bioleaching-market; Maia Research. "Global Bioleaching Market Dynamics and Major Player: TOP3 Companies Occupies a Market Share of 37.46%." Accessed August 21, 2025. https://www.maiaresearch.com/Press_Release/1856790.html.

Future market size heavily dependent on critical mineral demand and economics of biomining

Driver	Impact	Trajectory	Strategic Rationale
Demand for Critical Minerals	H	Increase	• Clean energy transition driving copper, nickel, cobalt, lithium demand; traditional sources insufficient • Main economic driver of bioleaching is recovery of critical metals like Cu, Al, Ni, Zn, Li, or U and REEs • Global transition to a circular economy calls for R&D on technologies facilitating sustainable resource recovery
Environmental/ ESG Pressures	M	Increase	• Regulatory pressure and social license requirements favoring lower-impact extraction methods • Bioleaching can stabilize sulphate toxins from the mine without causing harm to the environment • Bioleaching emerges as a promising eco-friendly and cost-effective alternative to traditional mining and metal recovery methods
Capital-Efficient Metal Recovery	M	Increase	• E-waste, tailings, and low-grade ore processing offering better economics than new mines • Microbial leaching methods being increasingly applied for metal recovery from low-grade ores and concentrates that cannot be processed economically by conventional methods • Electronic scraps represent an attractive raw material to mine demanded metals, as well as rare earth elements
Technology Maturation	M	Increase	• Advanced biotechnology and process improvements making biomining more commercially viable • Recent advances in biomining such as gene libraries, PCR-based techniques are promising for better understanding of microbial dynamics • Recent advances in biomining such as optimization of new influencing parameters such as micro-cracks
Geopolitical Supply Chain Risks	H	Increase	• Western governments pushing domestic/allied processing capabilities as strategic priority • China accounts for 85-90% of global rare earth element mine-to-metal refining and refines 68% of the world's cobalt, 65% of nickel, and 60% of lithium • US was 100% net import reliant for 12 of the minerals on the critical list and had net import reliance greater than 50% for an additional 28 commodities

Sources: García-Balboa, Carlos, Vanesa Martínez-Martínez, Francisco Quirós-Collazos, Luis González-Fernández, Jesús González-López, Antonio Pozo-Antonio, Tomasa Martín-Palma, and Ricardo Amils. "Microbial biominers: Sequential bioleaching and biouptake of metals from electronic scraps." MicrobiologyOpen 11, no. 1 (February 2022). https://doi.org/10.1002/mbo3.1265; Anglo American. "Bioleaching (Biomining) Advantages, Process & More." July 11, 2019. https://www.angloamerican.com/futuresmart/stories/our-industry/mining-explained/mining-terms-explained-a-to-z/bioleaching-definition-and-process.; Kara, Ilayda Tezyapar, Klaus Kremser, and Frédéric Coulon. "Bioleaching metal-bearing wastes and by-products for resource recovery: a review." Environmental Chemistry Letters 21, no. 6 (August 2, 2023): 3329-3350. https://doi.org/10.1007/s10311-023-01611-4; Bosecker, Klaus. "Bioleaching: metal solubilization by microorganisms." FEMS Microbiology Reviews 20, no. 3-4 (July 1997): 591-604. https://doi.org/10.1111/j.1574-6976.1997.tb00340.x; Roberto, Francisco F., and Axel Schippers. "Progress in bioleaching: part B, applications of microbial processes by the minerals industries." Applied Microbiology and Biotechnology 106, no. 16 (August 2022): 5913-5928. https://doi.org/10.1007/s00253-022-12085-9; Goldman Sachs. "Resource realism: The geopolitics of critical mineral supply chains." September 13, 2023. https://www.goldmansachs.com/insights/articles/resource-realism-the-geopolitics-of-critical-mineral-supply-chains; GovFacts. "Critical Minerals: US Strategy to Break China's Supply Chain Dominance." Accessed August 21, 2025. https://govfacts.org/analysis/critical-minerals-us-strategy-to-break-chinas-supply-chain-dominance/.

Biomining is well-established for a small number of metals, but emerging as a broader production method

Mineral	% global production[1]	Biomining maturity[1]	Primary technology
Copper	~10-15%	Mature	Bioleaching
Gold	~5%	Mature	Biooxidation (pretreatment)
Nickel	Very low; <1%	Emerging	Bioleaching
Zinc	Very low; <1%	Emerging	Bioleaching
Cobalt	Very low; <1%	Emerging	Bioleaching
Uranium	Very low; not clearly quantified	Emerging	Bioleaching
REEs	Experimental; not yet significant	Experimental	Bioleaching

Note: Detailed 2024 production breakdowns by extraction method are not systematically published by industry bodies. Estimates are derived from selective facility data, historical projections, and technical reviews rather than comprehensive industry metrics. Only copper and gold have well-documented global percentages. Others are estimates at this time

1. Estimates based on available data.

Sources: American Geosciences Institute. "What is biomining?" Professional FAQ. Accessed August 21, 2025. https://profession.americangeosciences.org/society/intersections/faq/what-biomining/; Johnson, D. Barrie. "Biomining—biotechnologies for extracting and recovering metals from ores and waste materials." Current Opinion in Biotechnology 30 (December 2014): 24-31. https://doi.org/10.1016/j.copbio.2014.04.010; Roberto, Francisco F., and Axel Schippers. "Progress in bioleaching: part B, applications of microbial processes by the minerals industries." Applied Microbiology and Biotechnology 106, no. 16 (August 2022): 5913-5928. https://doi.org/10.1007/s00253-022-12085-9; TriplePundit. "From the Petri Dish to the Mine: These Microbes Dissolve Minerals." 2024. https://www.triplepundit.com/story/2024/biomining-clean-energy/809756.

Established players have specialized in certain minerals, while startups are investing across multiple commodities

Mineral	Experimentation	Industrial scale mining	Processing / refining
Copper	BacTech Environmental; Transition Biomining; mint; 1849BIO	CODELCO; BHP	
Gold	BacTech Environmental; mint		Sibanye Stillwater; Pan African Resources
Nickel	BacTech Environmental	Terrafame	Terrafame; Elementis
Zinc		Terrafame	Terrafame
Cobalt	BacTech Environmental	Terrafame	Terrafame
Uranium[1]	CNNC	Kazatomprom	
REEs	Alta; Lawrence Livermore National Laboratory; Cornell University; mint		

1. The China National Nuclear Corporation is likely the entity referred to in a 2024 IAEA report regarding uranium bioleaching in China. Kazatomprom conducts industrial scale mining, but through microbial enhanced ISR (not marketed as biomining)

Sources: American Geosciences Institute. "What is biomining?" Professional FAQ. Accessed August 21, 2025. https://profession.americangeosciences.org/society/intersections/faq/what-biomining/; Johnson, D. Barrie. "Biomining—biotechnologies for extracting and recovering metals from ores and waste materials." Current Opinion in Biotechnology 30 (December 2014): 24-31. https://doi.org/10.1016/j.copbio.2014.04.010; Roberto, Francisco F., and Axel Schippers. "Progress in bioleaching: part B, applications of microbial processes by the minerals industries." Applied Microbiology and Biotechnology 106, no. 16 (August 2022): 5913-5928. https://doi.org/10.1007/s00253-022-12085-9; TriplePundit. "From the Petri Dish to the Mine: These Microbes Dissolve Minerals." 2024. https://www.triplepundit.com/story/2024/biomining-clean-energy/809756. International Atomic Energy Agency. Nuclear Technology Review 2024. GOV/2024/39-GC(68)/INF/4. Vienna: IAEA, 2024.https://www.iaea.org/sites/default/files/gc/gc68-inf-4.pdf

Biomining is a global industry

Biomining is a global industry with established commercial operations spanning multiple continents. **Leading markets include Chile, Finland, and South Africa**, which have achieved large-scale industrial deployment, sustained government investment, and pioneering technology development

Emerging markets - including New Zealand, China, and Iran- are rapidly scaling biomining applications through industry partnerships and pilot projects targeting battery metals and waste processing

Meanwhile, the **United States and Canada serve as primary innovation hubs** - with each investing in research on biomining applications for critical minerals and sustainable extraction technologies

Sources: See detailed pages for sources used

Established markets

Emerging markets

Innovation hubs

Established markets are home to scaled biomining operations

Chile: Copper Bioleaching at Scale

Radomiro Tomic Mine (CODELCO)

- Production: 250K tons / year
- Significance: Can enable turnaround of declining production

Escondida Mine (BHP)

- Production: ~36M tons / year
- Significance: Demonstrates technology utilized at industrial scale

Finland: Europe's Largest Biominer

Terrafame (Finnish Minerals Group)

- Minerals: Nickel, Zinc, Cobalt
- Production: ~30K tons / year (nickel); ~55K tons / year (zinc)
- Significance: Can operate in extreme climates (sub-arctic conditions) and is sustainable (~60% less carbon emissions vs. traditional nickel production)

South Africa: Gold Biomining Pioneer

Fairview Mine (Barberton Mines)

- Production: ~80k oz annually
- Significance: Unlocks "impossible" resources by changing economics

BIOX Technology (Metso)

- > 22M oz of gold produced
- 13+ successful BIOX mines commissioned

Sources: Mining Technology, "Radomiro Tomic Copper Mine" (January 2020); International Mining, "BHP on Escondida's pathways for growth" (November 2024); Terrafame company reports (terrafame.com); Kitco News, "Finnish nickel producer Terrafame to start uranium recovery in 2024" (December 2022); Pan African Resources, "Barberton Mines" (October 2024); Metso, "BIOX Process" documentation; Progress in bioleaching, PMC (2022); Innovations in Copper, "Producing copper nature's way: Bioleaching," copper.org (May 2004). ChatGPT used to create images.

Emerging markets are demonstrating ability to scale different types of biomining technology

New Zealand: E-waste pioneer

Mint Innovation (Sydney)

- Production: ~600kg (gold), ~600t (copper) annually from 3,000t of e-waste
- Significance: World's first urban, commercial biomining operation. Demonstrates profitable model for e-waste recovery. Expanded operations and opened a Texas facility in 2025

China: Bioheap leaching scaler

Zijinshan Copper Mine

- Production: ~20k tons annually (copper cathode)
- Significance: One of the world's largest bioheap operations. Proves commercial viability of processing ultra-low-grade ore (~0.15-0.25%) that would not be tenable with conventional methods

Iran: Industrial tank bioleaching leader

Iran Babak Copper Company (IBBCo)

- Production: ~50k tons annually (copper cathode)
- Significance: One of the world's largest tank bioleaching operations., using moderately thermophilic bacteria in a controlled environment. Demonstrates technology viability in arid environments

Sources: Resource Recycling. "Smelter alternative gears up for US entrance." October 17, 2024. https://resource-recycling.com/e-scrap/2024/10/17/smelter-alternative-gears-up-for-us-entrance/. Mint Innovation. "About." Company Website, 2024. https://www.mint.bio/about. Mint Innovation. "Technology." Company Website, 2024. https://www.mint.bio/solutions/technology. Mint Innovation. "Mint Innovation announces US sites for safe, sustainable electronics recycling." Company Website, 2024. https://www.mint.bio/mint-innovation-announces-us-sites. Ruan, Renman, Jinkang Wen, and Jianhang Chen. "Bacterial heap-leaching: Practice in Zijinshan copper mine." Hydrometallurgy 83, no. 1-4 (2006): 77-85. https://doi.org/10.1016/j.hydromet.2006.03.063. Wang, Sheng. "Copper Bioleaching in China: Review and Prospect." Minerals 8, no. 2 (2018): 32. https://doi.org/10.3390/min8020032. Liu, Xingyu, Bowei Chen, Jianhang Chen, Mingjun Zhang, Jiankang Wen, Dazhi Wang, and Renman Ruan. "Spatial variation of microbial community structure in the Zijinshan commercial copper heap bioleaching plant." Minerals Engineering 94 (2016): 76-82. https://doi.org/10.1016/j.mineng.2016.05.011. Roberto, Francisco F., and Axel Schippers. "Progress in bioleaching: part B, applications of microbial processes by the minerals industries." Applied Microbiology and Biotechnology 106, no. 16 (2022): 5913-5928. https://doi.org/10.1007/s00253-022-12085-9.). ChatGPT used to create images.

Innovation hubs use different models for investing in biomining technology advancement

United States: R&D leader but commercial scale laggard

- Approach: Sector development concentrated in start-ups backed by venture capital & government pilots
- Gov't programs: DARPA EMBER ($4.6M Phase 2), NSF Emerging Frontiers Program ($30M)
- Start-ups: Alta Resource Technologies, 1849 bio, Transition Biomining

Canada: Home to strong industry & academic R&D partnership

- Approach: Mining industry and academic partnerships focused on practical applications
- Mining firms' funding for academia: Vale (C$875K), Teck Resources (C$2M)
- Start-ups: BacTech Environmental; otherwise, limited start-up ecosystem

Key takeaways

- North America serves as a **hub for biomining research,** although commercial scaling of the technology is limited
- The **U.S. and Canada follow two distinct models** for funding innovation:
  - U.S. model relies on large government programs and private funding
  - Canadian model is based on targeted corporate allocations to universities
- Additional investment is likely required to scale biomining sectors in these countries

Sources: U.S. Department of Defense, Defense Advanced Research Projects Agency. *Environmental Microbes as a Bio-Engineering Resource (EMBER).* Program Summary, 2021. U.S. National Science Foundation. *Emerging Frontiers in Research and Innovation (EFRI) Program.* Program Overview, 2023. Business Wire. "Alta Resource Technologies Expands Series Seed Funding to $10M to Scale Protein-Based Critical Minerals Technology." Press Release, May 5, 2025. https://www.businesswire.com/news/home/20250505411471/en/Alta-Resource-Technologies-Expands-Series-Seed-Funding-to-$10M-to-Scale-Protein-Based-Critical-Minerals-Technology. Vale. "Vale Advances Circular Mining in Ontario with MIRARCO." Press Release, May 6, 2024. https://vale.com/w/vale-advances-circular-mining-in-ontario-with-mirarco.University of British Columbia. "UBC Applied Science and Teck Announce $4M for Mine Tailings Research and Education." News Release, April 19, 2019. https://give.ubc.ca/news/ubc-applied-science-and-teck-announce-4m-for-mine-tailings-research-and-education/. Images generated with ChatGPT.

Key takeaways: Current state & market

Biomining is a niche market (~$2 billion in 2024) compared to the global mining industry (~$4 trillion in 2024). In other words, it represents less than 0.05% market share of the overall mining industry. Notably, the sector faces uncertain growth, likely largely driven by demand for critical minerals, technology expansion of biomining to other commercial applications, and additional government investment

Despite its comparatively small size, biomining is a global industry. Certain countries – and commodities like copper and gold – are leaders in the sector. Chile, Finland, and South Africa have successfully commercialized the technology, and emerging markets like China and New Zealand are investing in scaling different biomining techniques

The innovation hubs of the U.S. and Canada have different approaches to investing in technological advancement; the U.S. relies on government pilots and private capital while Canada's ecosystem is driven by industry-academia partnerships. Start ups like Alta Resource Technologies and BacTech are experimenting with applying biomining techniques to new minerals like rare earth elements (REEs), although such efforts are still in the experimentation and prototyping phase

Source: McKinsey & Company. "Global Materials Perspective 2024." McKinsey Global Energy & Materials Practice, September 17, 2024. https://www.mckinsey.com/industries/energy-and-materials/our-insights/global-materials-perspective.

U.S. POSITION & INVESTMENT

Summary of current U.S. position on biomining and barriers to continued sector growth

The U.S. is a center for biotech innovation, but is still developing its biomining sector

The U.S. hosts **at least 9 biomining startups**, which is the largest cluster globally of the 27 identified start ups in the sector. Examples include Alta Resource Technologies, 1849 Bio, and Transition Biomining. However, **no domestic, commercial-scale biomining facilities exist** for copper, cobalt, gold, or nickel

U.S. federal support for biomining remains fragmented, with funding split between different agencies and various pilot programs

- DARPA EMBER- protein-based REE separation research
- NSF Emerging Frontiers - biomining-relevant projects, including synthetic biology, protein-based separation, and biogeochemical process engineering

The **U.S. stands in contrast to established markets** like Chile, Finland, and South Africa – where biomining has reached industrial scale. The barriers in the U.S. contributing to this difference include **regulatory fragmentation, capital reluctance, and an underdeveloped domestic mining industry**

Sources: Tracxn. "Startups in Biomining." Tracxn. Accessed August 25, 2025. https://tracxn.com/d/trending-business-models/startups-in-biomining/__wtU6END2PNkQW17z0g8Q0NgHsfSnXyp_yunzsULE7zs/companies. National Science Foundation. "Emerging Frontiers in Research and Innovation (EFRI) Program." NSF Award Database, 2023. Lawrence Livermore National Laboratory. "Concentrating on Rare-Earth Elements." August 14, 2024. https://www.llnl.gov/article/51036/concentrating-rare-earth-elements. U.S. Department of Energy, ARPA-E. "Critical Minerals and Materials Program Overview." U.S. DOE, 2023. Defense Advanced Research Projects Agency (DARPA). "Environmental Microbes as a BioEngineering Resource (EMBER)." Program Summary, 2023. International Mining. "Codelco's Radomiro Tomic Copper Mine in Chile to Use Bioleaching to Help Extend Its Life to 2030." March 17, 2021. https://im-mining.com/2021/03/17/codelcos-radomiro-tomic-copper-mine-chile-use-bioleaching-help-extend-life-2030/. Terrafame. "Company." Corporate Website, 2024. https://www.terrafame.com/company.html. Sibanye-Stillwater. *Integrated Report 2023*. Johannesburg: Sibanye-Stillwater, 2023. https://www.sibanyestillwater.com

Start-ups thrive in the U.S. environment, but other countries have better support for scaled businesses

U.S. biomining start ups are focused on diverse technologies:

- *Protein & enzyme-based separation:* Alta, REEgen, Maverick Biometals
- *Engineered microbes:* 1849 Bio, Transition Biomining
- *E-waste & tailings recovery:* Universal BioMining, Deep BioMining, Metalplant

Start up accelerators have played a valuable role in incubating these companies. For example, both 1849 Bio and Transition Biomining teams were backed by Y Combinator

However, despite innovation depth, none have yet scaled beyond the pilot or laboratory stage. Most remain focused on demonstrating microbial or biochemical pathways, building IP portfolios, or securing venture capital to support future growth

Select U.S. biomining start ups

Alta

REEgen

MAVERICK METALS

Transition Biomining

1849BIO

Universal BioMining

DEEP BIOMINING

Metalplant

Sources: •Tracxn. "Startups in Biomining." Tracxn. Accessed August 25, 2025. https://tracxn.com/d/trending-business-models/startups-in-biomining/__wtU6END2PNkOW17z0g8O0NgHsfSnXyp_yunzsULE7zs/companies. Y Combinator. "1849 Bio." Company Profile, 2024. https://www.ycombinator.com/companies/1849-bio. Y Combinator. "Maverick BioMetals." Company Profile, 2024. https://www.ycombinator.com/companies/maverick-metals. Business Wire. "Alta Resource Technologies Expands Series Seed Funding to $10M to Scale Protein-Based Critical Minerals Technology." Press Release, May 5, 2025. https://www.businesswire.com/news/home/20250505411471/en/Alta-Resource-Technologies-Expands-Series-Seed-Funding-to-$10M-to-Scale-Protein-Based-Critical-Minerals-Technology. Global Venturing. "6 Startups Cleaning Up the Supply Chain of Rare Earth Metals." February 14, 2025.https://globalventuring.com/corporate/europe/6-startups-cleaning-up-the-supply-chain-of-rare-earth-metals/. Metal Tech News. "Endolith Ramps up Copper, Lithium Biomining." May 28, 2025. https://www.metaltechnews.com/story/2025/05/28/mining-tech/endolith-ramps-up-copper-lithium-biomining/2299.html

The U.S. government has supported various biomining pilots…

Agency	Funding	Details
NSF	~$30M	• Allocated to "biomining-relevant" projects, however, not specifically earmarked for biomining research
DARPA	~$4.6M	• Phase 2 Award to Lawrence Livermore National Lab (LLNL) for protein-based REE separation • Demonstrated U.S. defense interest in additional sources for REEs
ARPA-E	~$40M	• Small pilots under programs like "RECOVER," which allocated ~$40M for extracting critical materials from wastewater • Not explicitly allocated to biomining; however, covers tangential activities

While the U.S. provides funding through these pathways, it does not provide any dedicated commercialization incentives nor has it yet passed biomining-specific legislation

Sources: National Science Foundation. "Emerging Frontiers in Research and Innovation (EFRI) Program." NSF Award Database, 2023. Lawrence Livermore National Laboratory. "Concentrating on Rare-Earth Elements." August 14, 2024. https://www.llnl.gov/article/51036/concentrating-rare-earth-elements. U.S. Department of Energy, ARPA-E. "Critical Minerals and Materials Program Overview." U.S. DOE, 2023. Defense Advanced Research Projects Agency (DARPA). "Environmental Microbes as a BioEngineering Resource (EMBER)." Program Summary, 2023. Cornell University College of Engineering. "Biomining Rare-Earth Elements." Research Spotlight, 2024.

…but there is a funding and regulatory gap compared with conventional mining companies

Federal support for biomining is research-heavy; it is focused on supporting R&D efforts and lab-scale projects. The entities providing the funding for R&D – DARPA, ARPA-E, NSF - are inherently research focused, and it is logical that the funding they provide would go towards R&D. However, the U.S. biomining sector is currently missing funding to support scaling and production of biomining technology.

In contrast, the U.S. government has invested in the production and scaling of conventional mining technologies. The U.S. government purchased ~$400M of MP Materials equity, in addition to offering the company a ~$150M loan for REE processing and magnet production. MP Materials is a conventional miner, and is receiving an order of magnitude different of capital

Additionally, biomining is not covered in legislation in the same way as conventional mining and processing – despite its potential to serve as another source of critical minerals and contribute to U.S. national security. Instead, DOE and DoD strategic minerals programs prioritize chemical refining and supply chain onshoring

Sources: MP Materials. "MP Materials Announces Transformational Public-Private Partnership with the Department of Defense to Accelerate U.S. Rare-Earth Magnet Independence." Press Release, July 10, 2025. https://investors.mpmaterials.com/investor-news/news-details/2025/MP-Materials-Announces-Transformational-Public-Private-Partnership-with-the-Department-of-Defense-to-Accelerate-U-S--Rare-Earth-Magnet-Independence/default.aspx. U.S. Department of Defense. "Mine-to-Magnet Supply Chain Investment." DoD Press Release, July 2025. New Jersey Institute of Technology. "Bipartisan Infrastructure Law (BIL): Battery Materials Processing and Manufacturing Programs." 2023. https://research.njit.edu/bipartisan-infrastructure-law-bil-battery-materials-processing-and-battery-manufacturing. Lift & Access. "Bipartisan Infrastructure Law Boosts Domestic Battery Supply Chains." February 1, 2023. https://www.liftandaccess.com/article/316-billion-bipartisan-infrastructure-law-boost-domestic-battery-supply-chains.

There is an opportunity to build the U.S. biomining sector

As countries like Chile, Finland, and South Africa have proven, there is an economic opportunity in biomining:

- Transforming waste to potential resources: Mine tailings, coal ash, and e-waste have the potential to become new sources of copper, nickel, cobalt, REEs, and other critical minerals
- Potential to leverage Mint Innovation to learn from implementation in New Zealand on e-waste processing

The U.S. also has a number of comparative advantages it should leverage:

- *Established biotech industry:* The U.S. has a history of biotech innovation – particularly in the fields of engineered microbes, synthetic biology, and protein separation technologies
- *ESG and community acceptance:* Biomining tends to be environmentally friendly than traditional mining methods, making it potentially more palatable to American communities
- *Deployment model:* There is potential for a small facility footprint that can be located across the mining value chain (e.g., at mine tailings, recycling centers, or other distribute supply hubs)

Finally, the political environment is promising for building biomining in the U.S. at this moment. The Trump administration is supportive of efforts to build U.S. critical mineral security – and may be more willing to put funding behind biomining as an opportunity to strengthen U.S. access to critical minerals

Sources: • Johnson, D. Barrie. "Biomining—Biotechnologies for Extracting and Recovering Metals from Ores and Waste Materials." Current Opinion in Biotechnology 30 (December 2014): 24–31. https://doi.org/10.1016/j.copbio.2014.04.010. Roberto, Francisco F., and Axel Schippers. "Progress in Bioleaching: Part B, Applications of Microbial Processes by the Minerals Industries." Applied Microbiology and Biotechnology 106, no. 16 (August 2022): 5913–5928. https://doi.org/10.1007/s00253-022-12085-9. Anglo American. "Bioleaching (Biomining): Advantages, Process & More." July 11, 2019. https://www.angloamerican.com/futuresmart/stories/our-industry/mining-explained/mining-terms-explained-a-to-z/bioleaching-definition-and-process.

However, the U.S. must overcome existing barriers to do so

1. Investor uncertainty
Uncertain market growth projections (~$2.4B compared to ~$3.6B) as well as the relatively small market size (~$1.8B in 2024) create investor uncertainty

2. Capital reluctance
Bioleaching – like other mining sectors – has a long-term ROI. Building a bioleaching facility and seeing profits may take ~10-20 years. High technical risk increases reluctance

3. Industry conservatism
Biomining at scale within the domestic U.S. remains unproven – and industry is not incentivized to take the bet. Proven methods (and economics) remain preferred

4. Regulatory fragmentation
There is no direct biomining permitting pathway in the U.S. Additionally, overlapping jurisdiction between agencies (e.g., EPA, DOE) increases delays for approvals

5. Technical risks
Bioleaching is not without risks – acid mine drainage, bioreactor containment failures, and community opposition are all risks associated with biomining operations

Sources: Credence Research. Bioleaching Market Size, Growth, Share and Forecast 2032. November 15, 2024. https://www.credenceresearch.com/report/bioleaching-market. Maia Research. Global Bioleaching Market Dynamics and Major Player: TOP3 Companies Occupies a Market Share of 37.46%. Accessed August 21, 2025. https://www.maiaresearch.com/Press_Release/1856790.html. S&P Global Market Intelligence. "PE Deals in Metals & Mining Set to Pick Up as Critical Mineral Demand Rises." May 2025. https://www.spglobal.com/market-intelligence/en/news-insights/articles/2025/5/pe-deals-in-metals-mining-set-to-pick-up-as-critical-mineral-demand-rises-88722991. U.S. Government Accountability Office. National Defense Stockpile: Actions Needed to Improve DOD's Efforts to Prepare for Emergencies. GAO-24-106959, September 10, 2024. https://www.gao.gov/products/gao-24-106959. Roberto, Francisco F., and Axel Schippers. "Progress in Bioleaching: Part B, Applications of Microbial Processes by the Minerals Industries." Applied Microbiology and Biotechnology 106, no. 16 (August 2022): 5913–5928. https://doi.org/10.1007/s00253-022-12085-9. U.S. Department of the Interior. 2025 List of Critical Minerals. U.S. Geological Survey, February 2022.

RECOMMENDATIONS & PATH FORWARD

Summary of recommendations to support growth of U.S. biomining sector

Policy Framework for U.S. Biomining Leadership

1. Tax and Financial Incentives

TREASURY Issue guidance extending Section 48D to biomining facilities as "qualifying advanced energy projects"

CONGRESS Amend IRC Section 45X to include bioprocessed minerals in Advanced Manufacturing Production Credit

2. Regulatory Streamlining

EPA Designate as lead agency for NEPA reviews and issue general permits for facilities <100 tons per year

CEQ Establish Biomining Task Force and 12-month NEPA timeline for projects under $50M

3. Leveraging Existing Federal Programs

DOE Add biomining to Title XVII Loan Guarantee Program eligible technologies list

EXIM Include biomining in CTEP program guidance per EO Section 6(f) mandate

Federal Investment Strategy to Catalyze U.S. Biomining

DOE Loan Program Office

$200M

Title XVII authority for 3 commercial demonstration facilities processing copper, lithium, and REEs from waste streams

ARPA E Scalable Program

$100M

Next-generation biomining technologies including engineered microbes and protein separation

DOD Via DPA Title III

$150M

Direct investment in biomining of defense-critical minerals (REEs, lithium, cobalt) using existing Section 303 authorities

ARPA E Scalable Program

$50M

University-industry consortiums modeled on successful Canadian partnerships

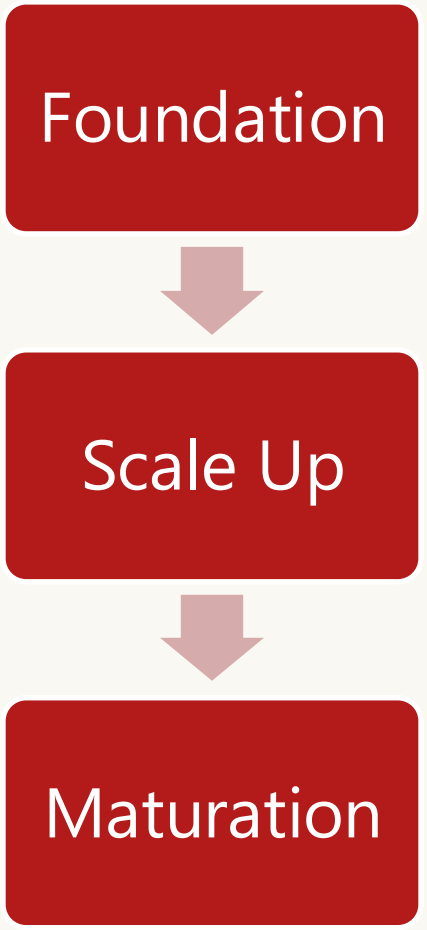
Beyond direct funding, the federal government should de-risk private investment through loan guarantees and offtake agreements. The DOE Loan Programs Office can provide 80% guarantees for the first five commercial facilities, while the Defense Logistics Agency commits to purchasing bioprocessed minerals at a 15% premium for the National Defense Stockpile.

Interagency Implementation Roadmap

Phase 1: Foundation (Lead: White House OSTP) In Phase 1, the Department of Energy (DOE) will select three demonstration sites through a competitive FOA in Q2 2025. The State Department will negotiate technology transfer MOUs with Finland's Terrafame and with Australia. The Department of Commerce will partner with Mint Innovation to establish a U.S. e-waste facility, while the Environmental Protection Agency (EPA) will issue compliance guidance for biomining operations.

Phase 2: Scale Up (Lead: DOE) In Phase 2, the Department of Defense (DOD) will fund the first commercial biomining facility, producing 10,000 tons of copper or 1,000 tons of rare earth elements annually. The Defense Logistics Agency (DLA) will incorporate biomining products into the National Defense Stockpile. The Department of Labor will launch a $50 million community college program to train a biomining workforce, and the U.S. Geological Survey (USGS) will complete a national assessment of waste resources suitable for biomining.

Phase 3: Market Maturation (Lead: Commerce) In Phase 3, the Export-Import Bank (EXIM) will finance $100 million in biomining technology exports to allied nations. The U.S. Trade Representative (USTR) will negotiate biomining provisions in critical minerals agreements, while the DOE will work to achieve 10% domestic processing of critical mineral imports. Finally, the National Security Council (NSC) will integrate biomining into the National Security Strategy to strengthen supply chain resilience.



Conclusion

The U.S. paradox: global leader in biomining innovation (9 startups, strong biotech R&D) yet zero commercial operations while Chile processes 10% of its copper through biomining.

The Real Opportunity: Not just breaking China's mineral monopoly, but transforming stranded assets—millions of tons of mine tailings and growing e-waste—into strategic resources using technology the U.S. already pioneers.

Critical Barriers:

- Risk-averse capital markets for 10-20 year returns
- Fragmented federal approach (research funded, commercialization orphaned)
- Mining industry conservatism despite proven international success

The Path: Beyond funding, success requires coordinated federal leadership, regulatory certainty, and bridging the valley of death between U.S. innovation and industrial deployment.

Bottom Line: Biomining offers a near-term pathway to mineral independence that plays to American strengths. The window is now—before competitors capture this market while political support remains strong.