

How big is biominining?

A first estimate of the sector, its potential from waste, and where biology could take rare earths.

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The headline

2020 • BENCHMARK

\$2.6bn a year

Copper, nickel, zinc and cobalt in the 2020 benchmark, valued at reference prices.

ILLUSTRATIVE DEPLOYMENT SCENARIO

\$4.8bn a year

From tailings and battery waste, at reference prices. Range \$1.2bn–\$12bn by site count; ~\$6bn at copper \$13,000/t and cobalt \$55,000/t.

Gross product value before costs. Reference prices: copper \$8,500/t, cobalt \$40,000/t. Some biological recovery could replace conventional recovery rather than add to it.

What changed since 2020

PRICE

Copper above \$13,000/t

LME close, 30 July 2026.

POLICY

Cobalt export quotas

The DRC now caps exports.
Cobalt was above \$56,000/t in
January 2026.

TECHNOLOGY

Nuton's first copper

Rio Tinto's bioleaching-based
technology, Arizona, December
2025.

SCALE

Terrafame: €556m sales

2025 company sales from an
operation based on biological
recovery (bioleaching), Finland.
Nickel sulphate capacity: enough for
~1 million EVs a year, by the
company's estimate.

What we know

2020 BENCHMARK	ANNUAL OUTPUT
Copper	~233,000 t
Zinc	55,100 t
Nickel	28,740 t
Cobalt	~600 t
Gold, with biological pretreatment	~67 t

Some copper came from mixed recovery routes, so biological attribution is imperfect.

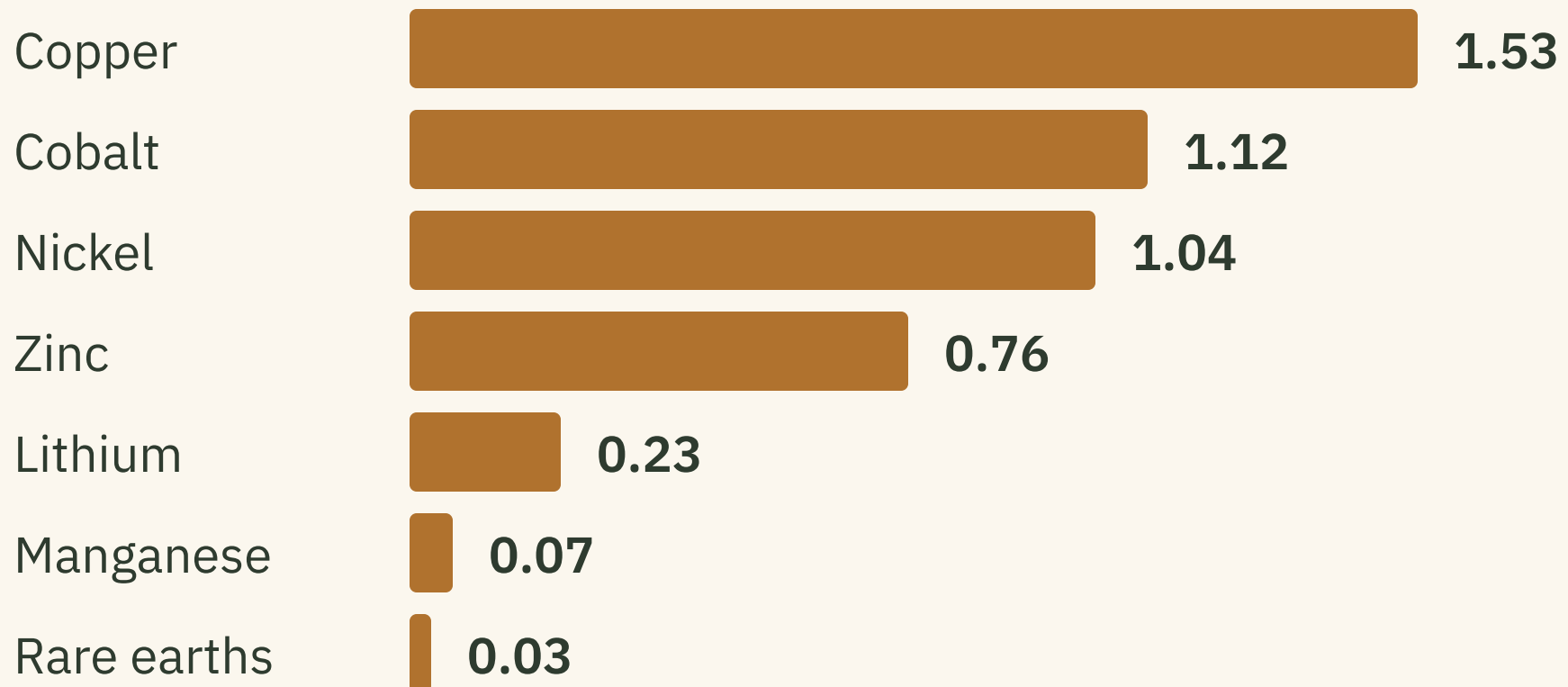
Latest site disclosures

Johnson Camp, Arizona: ~590 t of copper in August 2026. The release doesn't separate Nuton's share.

Terrafame, Finland: 14.9 Mt of ore mined in 2025. No per-metal output in the reports we reviewed.

Potential under our working assumptions

Working scenario at reference prices, \$bn a year. Total **\$4.8bn**.



Built from 645 assumed tailings reprocessing operations at 750,000 t a year each, plus 25 assumed biological or hybrid battery circuits at 10,000 t of black mass a year each. Gross value before costs.

Today's actual output is not counted: we found no harmonised count of biological metal production since the 2020 benchmark.

How far it could scale

Based on how many operations are built. Grades, recoveries and prices stay the same.

A QUARTER OF THE SITES

~160 tailings operations,
~6 battery circuits

\$1.2bn

WORKING SCENARIO

645 tailings operations,
25 battery circuits

\$4.8bn

2.5× THE SITES

~1,610 tailings operations,
~63 battery circuits

\$12bn

Price sensitivity: at copper \$13,000/t and cobalt \$55,000/t, the working scenario reaches ~\$6bn. Site counts are assumptions, not a census; this is a sensitivity, not a forecast.

The material is already out there

TAILINGS WORLDWIDE

~13bn t a year

of new tailings, by one 2021 estimate. Our 2.5× case would need ~1.2bn t a year: under a tenth.

WALES

2,500+

disused coal tips mapped by the Welsh Government.

POLAND

760Mt+

of hard-coal mining waste in 220+ dumps.

EUROPEAN UNION

~500Mt

of mining and quarrying waste in 2022 alone.

APPALACHIA

~1,000t a year

of rare-earth oxides estimated in mine-drainage sludge.

Volume isn't suitability. Grade, mineralogy, access and rights decide which sites qualify, and not all of this suits our scenario.

What would change these numbers

~\$7 of product per tonne

Tailings yield that before costs.
Can recovery revenue plus avoided remediation cover the full cost?

Cobalt-rich battery feed

88% of the cobalt comes from a battery sample at 19.75% cobalt. How much such feed will exist?

Sites that can sustain it

How many tailings operations hold these volumes, grades and saleable yields?

Operations we've missed

Who is running biological recovery at commercial scale today?

Why rare earths, why now

69%

of 2025 mine output
came from China

~90%

of processing
happens in China

10 Nov

2026: China's pause
on its Oct 2025
export controls ends

The value sits in a few elements

OXIDE	2025 PRICE, \$/T
Lanthanum	1,000
Cerium	1,710
Neodymium–praseodymium (NdPr)	69,000
Dysprosium	239,000
Terbium	1,010,000

Already in the waste

PHOSPHOGYPSUM

100Mt+

produced a year. An estimated ~100,000 t of rare earths a year end up in it.

BAUXITE RESIDUE

~140Mt

produced a year. One studied residue held ~300 ppm rare earths; at its prices, scandium carried ~99% of the value.

MINE DRAINAGE

~1,000t

of rare-earth oxides a year estimated in Appalachian treatment sludge.

ILLUSTRATION

At the ~25% leaching seen in the lab, the yearly phosphogypsum flow alone could release ~25,000 t of rare earths, in theory, before downstream recovery losses.

Indicative only. Lab leaching is not plant recovery.

Biology fits the problem

Rare earths in waste are often dilute and mixed with other metals. Early results suggest biology can help in those conditions.

01 It works on low-grade feeds

Lanmodulin, a natural protein, recovered rare earths from feedstocks containing only 1–2% rare earths, in fewer separation steps.

02 It fits hybrid processes

The EU BIORECOVER project paired bacterial leaching with microcapsules, recovering yttrium at 95% selectivity in synthetic solutions.

03 It works in mild conditions

Acids made by bacteria leached rare earths from phosphogypsum at 28 °C, without strong mineral acids.

The opportunity: biological steps that could make low-grade waste worth processing.

How far along it is

01 Leach

LAB

Bacterial acids dissolved ~25% of the rare earths in phosphogypsum over 21 days.

02 Recover

SEMI-PILOT

The EU BIORECOVER project recovered up to ~80% of yttrium and scandium (test solutions) and ~40% of neodymium.

03 Separate

LAB

Lanmodulin has separated rare earths in lab columns. Repeated cycles on real leachates still need testing.

We found no commercial biological rare-earth operation. What's missing is evidence at scale.

What it could become

Mixed rare-earth oxide value a year, before costs.

15 OPERATIONS

Our current model

\$34m

50 OPERATIONS

Same inputs per site

\$113m

100 OPERATIONS

Same inputs per site

\$225m

The mix decides the value

These use a \$15,000/t mixed basket. NdPr sold for \$69,000/t in 2025, dysprosium for \$239,000/t. Streams rich in them are worth many times more.

Each operation: 750,000 t of feed a year, 0.10% rare-earth oxide, 20% saleable yield.
Illustrative counts, not a site inventory.

What's holding it back

1 Does urgency favour established routes?

The EU funded BIORECOVER with a €6.3m research grant. The US backed MP Materials with a \$400m stake, a \$110/kg NdPr price floor and offtake commitments.

2 Do 2030 deadlines leave room for new routes?

EU 2030 targets: 10% mined, 40% processed and 25% recycled in the EU; no more than 65% from one country.

3 Can the evidence be compared?

Studies differ in feed, units and conditions, and few report a saleable product.

4 Is separation the bottleneck?

Separating similar rare earths to buyer specification is hard, and biology's best separation result is still at lab scale.

Each one is testable. Tell us your answer.

Help build the count

One dated site beats any assumption in this model. Send what you can:

-
- 01 Site and date
 - 02 Feed type and annual tonnes
 - 03 Head grade
 - 04 Saleable recovery
 - 05 Product and annual output
-

Send it to martin@bioseq.io. I'll share back what comes in, with the spreadsheet behind these numbers.

Sources

2020 benchmark (copper, cobalt, gold): 2022 review, Table 4. [pmc.ncbi.nlm.nih.gov](https://pubmed.ncbi.nlm.nih.gov)

Terrafame: 2020 nickel and zinc [results](#) · 2025 sales [results](#) · 2025 ore mined, [sustainability report](#) p.59 · EV capacity [release](#), Dec 2020

Johnson Camp, August 2026: Gunnison Copper, 22 Sep 2026. gunnisoncopper.com

Nuton first copper: Rio Tinto, 4 Dec 2025. riotinto.com

Copper price: LME close, 30 Jul 2026, 625.73 US\$/lb. miningreporters.com

Cobalt price and DRC export quotas: Ecofin Agency, Jan 2026. ecofinagency.com

Battery sample at 19.75% cobalt: University of Liège study. orbi.uliege.be

~13bn t of new tailings a year: Franks et al., Scientific Reports, 2021. nature.com

Wales, 2,500+ disused coal tips: Welsh Government. gov.wales

Poland, 760Mt+ in 220+ dumps: Gawor, Geology, Geophysics & Environment, 2014. journals.agh.edu.pl

EU mining and quarrying, 22.7% of 2.2bn t (2022): European Parliament. europarl.europa.eu

Appalachian mine-drainage rare earths: WV DEP and WVU, via ECOS, 2019. ecos.org

Reference prices: copper \$8,500/t, cobalt \$40,000/t, nickel \$16,000/t, zinc \$2,800/t, lithium carbonate \$12,000/t, manganese sulphate \$600/t, mixed rare-earth oxide \$15,000/t. Scenario model: Bioseq workbook v0.5, available on request.

Sources: rare earths

World and China output, La/Ce/NdPr prices, export controls: USGS Mineral Commodity Summaries 2026, Rare earths. pubs.usgs.gov

Dysprosium and terbium prices: USGS MCS 2026, Heavy rare earths. pubs.usgs.gov

Pause expiry (10 Nov 2026) and processing share: Mining Technology, 27 Apr 2026. mining-technology.com

~100,000 t of rare earths a year in phosphogypsum: Idaho National Laboratory, 2019. inl.gov

Phosphogypsum output; ~25% leaching with bacterial acids at 28 °C: Zhang et al., Molecules, 2025. pmc.ncbi.nlm.nih.gov

Bauxite residue output, rare-earth content, scandium value share: Reid et al., Scientific Reports, 2017. pmc.ncbi.nlm.nih.gov

Appalachian mine-drainage rare earths: WV DEP and WVU, via ECOS, 2019. ecos.org

BIORECOVER grant, scale, recoveries and microcapsule selectivity: CORDIS. cordis.europa.eu

Lanmodulin separation: Ames Laboratory / LLNL, July 2024. ameslab.gov

US stake and \$110/kg NdPr floor: MP Materials, 10 July 2025. mpmaterials.com

EU 2030 benchmarks: Council of the EU, Critical Raw Materials Act. consilium.europa.eu

~25,000 t illustration and 50/100-operation cases: Bioseq calculation from the figures above.

About

BIOSEQ

Bioseq is a UK company building AI-supported, evidence-governed intelligence for biological critical-mineral recovery. It tests published evidence against a specific material and route, finds candidate metals and biology in waste streams, and says plainly when the evidence doesn't hold.

Independent by design: no preferred route or technology to promote. **Bioseq is what you use before you spend on a pilot.**

THE AUTHOR

Martin Mantalvanos founded Bioseq in 2025. He has more than 25 years in technology entrepreneurship across Europe and Silicon Valley: CEO of RSM Technologies, founder and CEO of Hannah Systems in the San Francisco Bay Area, and Senior Partner at Nuccess in Ljubljana. He is the author of the Investing in AI series, including *The Critical Mineral Stack*.

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Scenario figures are illustrative: not forecasts, project valuations or investment advice.