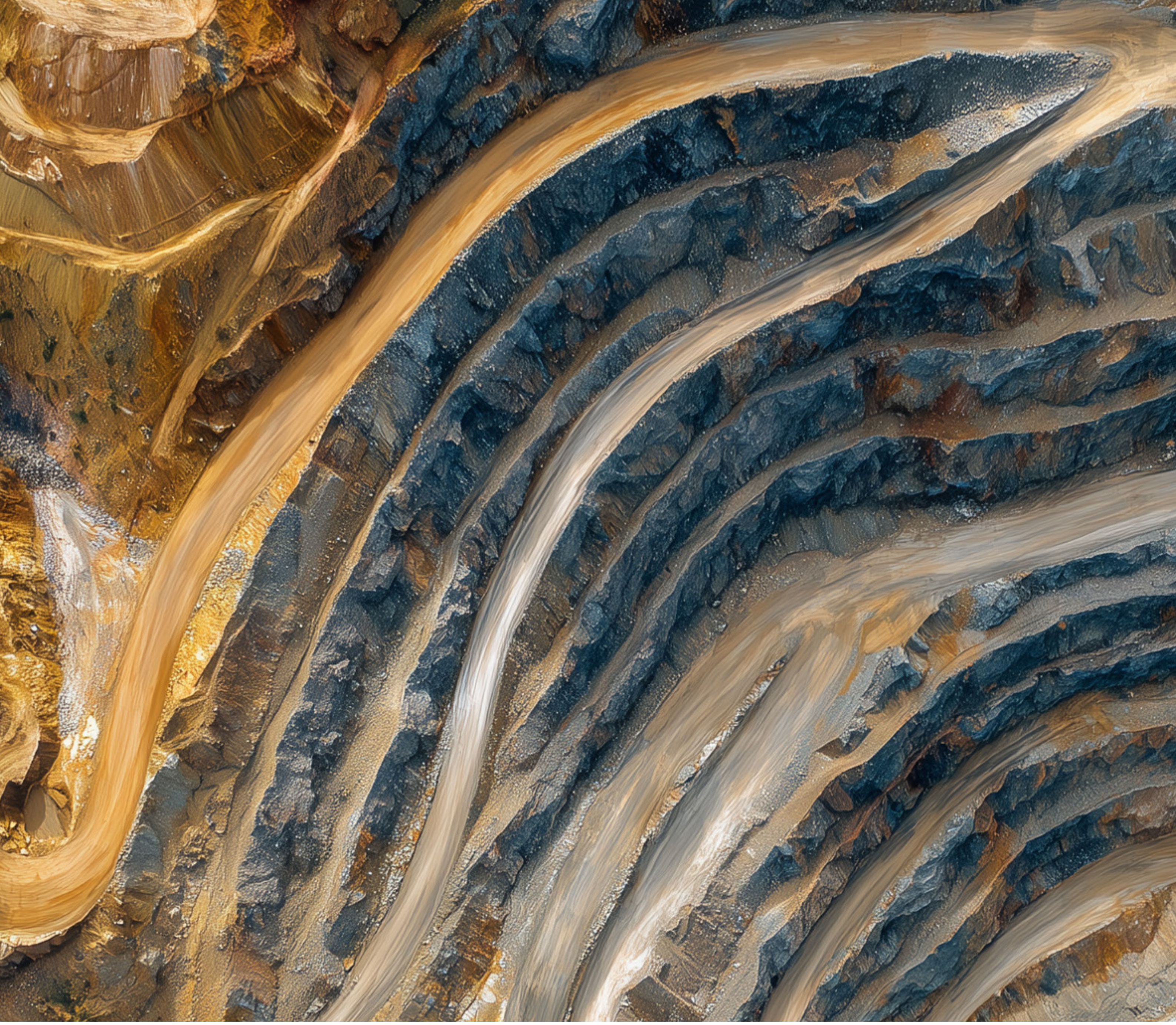

Beyond the drill: How biology is reshaping the mining industry

Bidra Nucleus Capital WORLD FUND Forbion.

Introduction

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Biomining

A paradigm shift

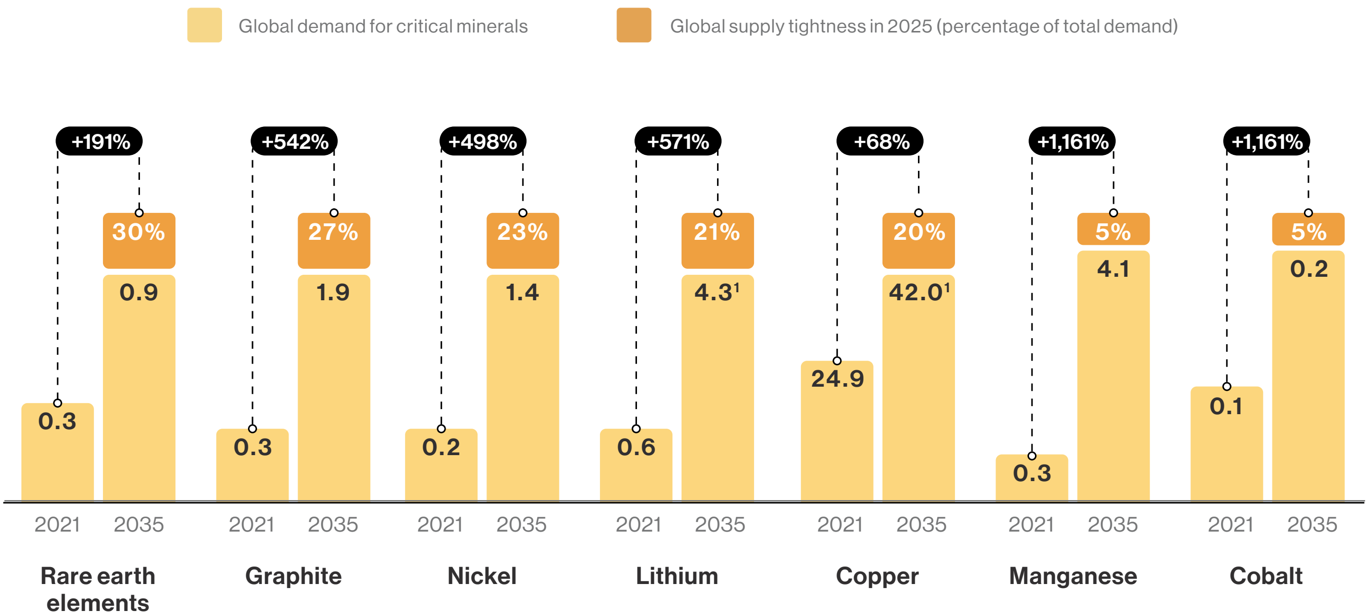
Structural shifts driving biomining

The mining industry is approaching a structural inflection point. Demand for critical minerals is accelerating, driven by electrification, grid expansion, battery manufacturing, and the rapid build-out of data centre infrastructure. At the same time, the constraints of conventional mining are intensifying. Ore grades are declining, energy and water requirements per tonne are rising, exploration spending has fallen, new discoveries are becoming rarer and deeper, and permitting timelines continue to lengthen.

By 2035, a 20% gap is expected between critical mineral demand and identified supply. This widening imbalance underscores the need for new extraction pathways capable of unlocking resources that are currently uneconomic or inaccessible.

Demand projections for critical minerals indicate that up to 20% of required supply sources have not yet been identified.

Global demand (millions of tons)



[1] This figure represents the uppermost extent of the estimated range of the supply shortage for this mineral (lithium or copper). The estimate is expressed as a range, due to the high degree of uncertainty surrounding this mineral.

Sources: US Geological Survey; World Bank; S&P Global; Wood Mackenzie; BCG analysis.

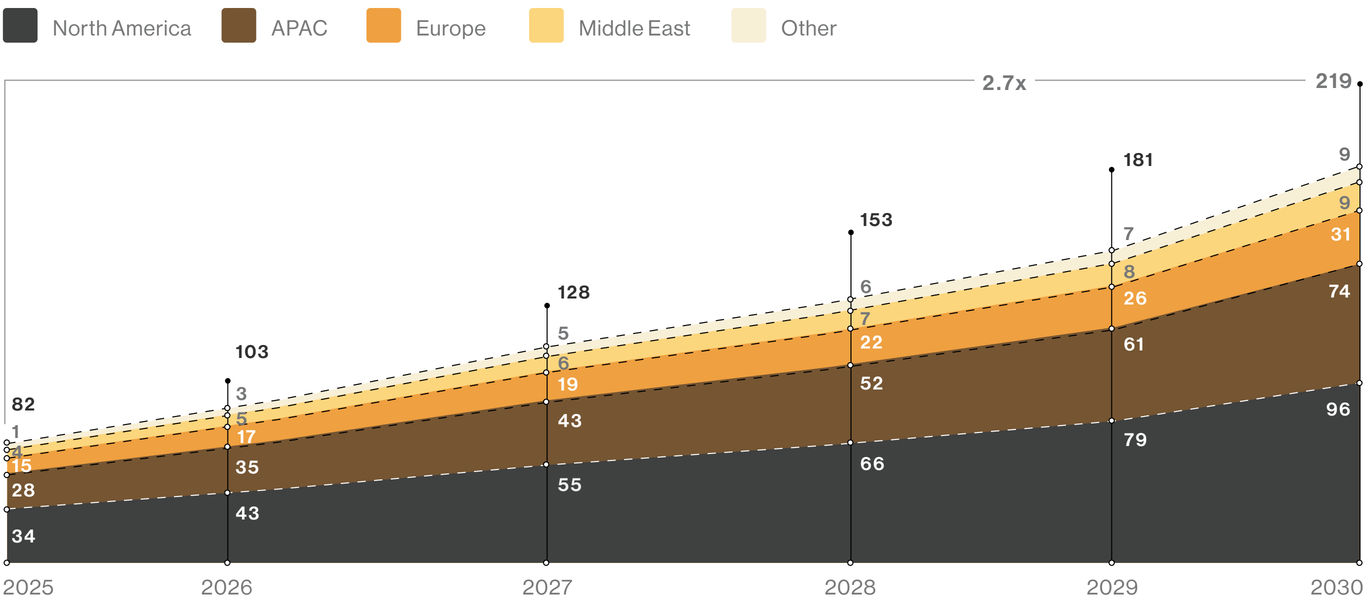
Historically, innovation in mining has focused on incremental improvements to established thermochemical processes. Smelting, roasting, pressure oxidation, solvent extraction, and electrowinning remain the backbone of metal production. While these approaches have scaled effectively, they are increasingly challenged by declining ore quality, rising costs, and environmental constraints.

Biomining introduces a fundamentally different approach. Rather than relying primarily on heat, pressure, and chemical reagents, it leverages biological systems—microorganisms, engineered proteins, plants, and fungi—to mobilise, concentrate, or selectively bind metals. This creates a potential pathway to improve recovery, reduce chemical intensity, and access lower-grade or previously stranded resources.

Biomining should not be viewed as a single technology, but as a spectrum of approaches with distinct roles across the mining value chain. In the near term, biological systems can function as process-intensification tools embedded within existing mining operations, improving recovery rates, reducing reagent consumption, and extracting value from tailings or low-grade sulphide ores. Over the longer term, emerging approaches such as phytomining introduce a different supply model, where metals are accumulated in plant biomass and harvested through agricultural processes. The convergence of rising resource constraints and rapid advances in biotechnology—including genomics, CRISPR-based engineering, and AI-assisted biological design—is moving biomining from academic exploration toward early commercial relevance.

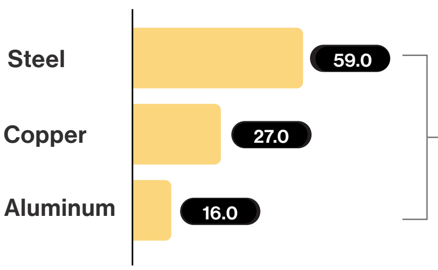
AI-driven data centre demand capacity drastically accelerates need for critical minerals

Global data center demand capacity by region, gigawatts

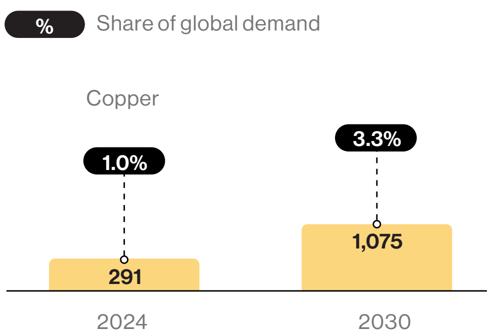


Demand intensity of materials required in data centers

Metric tons per megawatt (MW)



Global material demand from data centers, kilotons



Source: McKinsey & Company (2025), Global Materials Perspective 2025; adapted by authors

This white paper examines the technological landscape, commercial potential, and key considerations for investors and operators evaluating biomining opportunities.

Consortium rationale

Biomining requires combined expertise across biotechnology, mining operations, and industrial process engineering. Bidra Innovation Ventures, Nucleus Capital, World Fund, and Forbion BioEconomy formed a consortium to jointly assess the technology landscape, identify investable opportunities, and support startups in scaling from laboratory validation to field deployment.

This white paper has three primary objectives:

01	02	03
Provide a structured overview of biomining technologies	**Assess technical and economic relevance**	**Identify implications for ecosystem players**
We outline the principal biological approaches, including microbial leaching and bio-oxidation, protein-engineered separations, phytomining, and fungi-assisted systems, and map them across the mining value chain.	We examine where biological systems offer measurable advantages in recovery, cost, or environmental performance, and where scalability or operational risks remain material.	We analyse the emerging startup landscape, research hubs, and potential white spaces, and discuss the conditions required for successful industrial integration.

This white paper aims to provide private equity and venture capital investors, mining operators, and founders with a clear and coherent overview of innovation in biomining, as well as practical benchmarks and considerations for evaluating opportunities in the sector.

Four pressures reshaping how metals are extracted

Four structural developments underpin the growing relevance of biomining today:

01

Declining ore grades and rising marginal costs

A significant share of future copper and nickel supply will need to come from low-grade sulphide or lateritic deposits. Conventional processing of these resources is often energy- and capital-intensive, placing pressure on project economics.

Biological systems can improve recovery rates in heap leaching, enhance pretreatment of refractory ores, and unlock residual value from tailings and waste streams. Even modest improvements in recovery can materially impact project economics at scale, particularly for large operations processing low-grade material.

02

Geopolitical pressure and resource sovereignty

Critical mineral supply chains are increasingly concentrated geographically, particularly for nickel, cobalt, and rare earth elements. This concentration creates strategic vulnerabilities for importing regions.

Biomining offers a potential pathway to unlock more geographically distributed resources. Approaches such as phytomining could enable countries to access shallow, previously uneconomic deposits within their own borders, supporting domestic supply development with lower upfront capital requirements.

03

ESG pressure and permitting constraints

Mining projects face increasing scrutiny related to emissions, water usage, waste generation, and local environmental impact. In many jurisdictions, permitting timelines exceed a decade.

Technologies that reduce energy input, reagent consumption, or downstream waste management requirements can improve both environmental performance and regulatory acceptance. As a result, there is growing demand for lower-impact processing solutions that strengthen the permitting narrative and reduce lifecycle footprint.

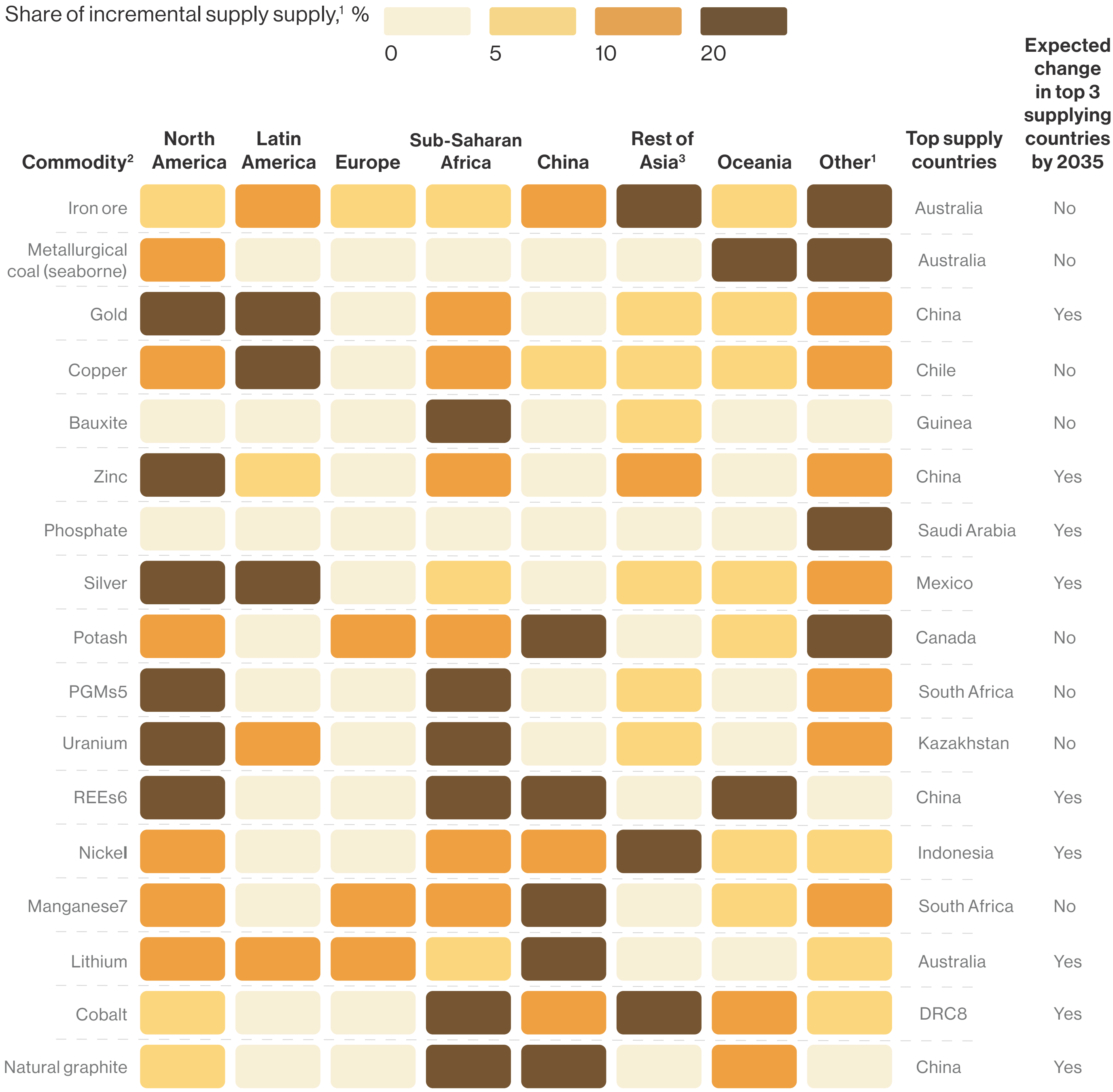
04

Maturation of biotechnology

The underlying biological toolkit has advanced significantly. Engineered microbial consortia can be tailored to specific ore bodies and operating conditions. Protein-based systems enable selective metal binding under hydrometallurgical conditions, and advances in monitoring and data analytics allow dynamic control of biological processes in industrial environments.

These developments are reducing historical constraints related to process stability, selectivity, and scalability, making biological approaches increasingly viable in industrial settings.

Announced projects of additional mining supply, 2035, high-case scenario



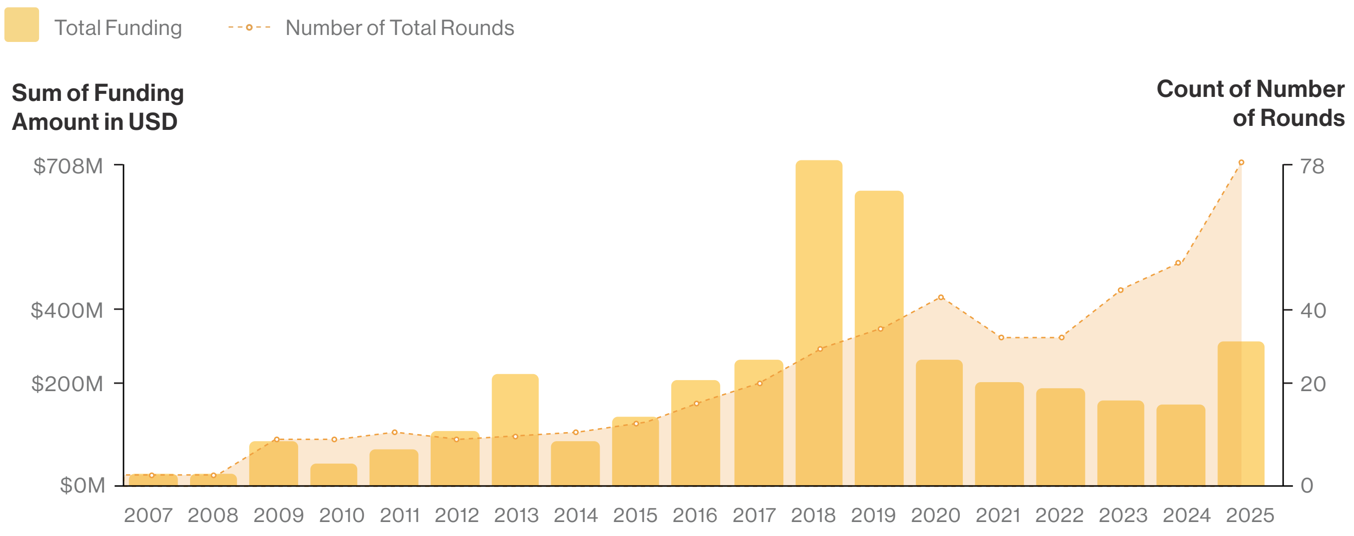
Source: McKinsey & Company (2025), Global Materials Perspective 2025; adapted by authors.

[1] Share of total announced projects' capacity increase between 2024 and 2035. [2] Excl steel and aluminum, which are refined products, and lead because of limitations in modeling. [3] India and other Asian countries. Commonwealth of Independent States and Middle East and North Africa. Platinum group metals, incl palladium, platinum, and rhodium, based on weighted average approach. Rare earth elements, incl dysprosium, neodymium, praseodymium, and terbium, based on weighted average approach. Total increase from regions with increased supply is <5%. Democratic Republic of the Congo. Source: McKinsey MineSpans

Biomining as a venture case

Mining has historically been underrepresented in venture portfolios due to long timelines, capital intensity, and exposure to commodity price cycles. However, given the emerging supply-demand gap, this stance has shifted significantly, with startups raising $3.5B between 2010 and 2025 (Tracxn, 2026) and gaining prominence; for example, see the top 50 mining startups according to Dealroom.

Funding activity in mining startups has accelerated since 2015



Source: Tracxn (2026), Mining Companies Investment Trends Dashboard; adapted by authors.

Importantly, biomining technologies are not competing head-on with the most productive conventional mines. Instead, they can unlock value in resource segments that are currently uneconomic. Examples include shallow soils unsuitable for conventional mining, legacy tailings with residual metal content, and low-grade sulphide deposits where recovery rates remain constrained. In this context, even modest improvements in biological recovery can materially improve project economics, shift cut-off grades, and unlock resources that would otherwise remain stranded.

The authors therefore see strong potential for biomining as a VC case:

01 Declining ore grades and rising marginal costs

Many biomining companies are technology-layer businesses rather than mine developers. They integrate into existing operations to improve yield, selectivity, or reagent efficiency. This reduces capital intensity relative to full-stack/greenfield mine development and enables faster pathways to deployment.

02 Geopolitical pressure and resource sovereignty

In large-scale mining operations, incremental improvements in recovery or reductions in reagent consumption can translate into significant financial impact. Technologies that increase recovery from low-grade ores or reduce downstream processing costs can unlock substantial value across existing asset portfolios.

03 Access to stranded resources

Biological systems can enable the economic processing of resources that are currently uneconomic, including tailings, low-grade sulphide deposits, and shallow soils unsuitable for conventional mining. This effectively expands the accessible resource base without requiring new large-scale infrastructure.

04 Alternative supply models

Some biomining approaches, most notably phytomining, introduce a fundamentally different production model. By replacing complex excavation with simpler agricultural processes, phytomining can reduce early-stage infrastructure requirements and shorten the path from site selection to first output, improving CAPEX intensity and shortening time-to-production.

Overall, biomining represents a hybrid opportunity: combining elements of industrial biotechnology, process optimisation, and resource extraction. The most attractive opportunities are likely to be those that demonstrate clear integration pathways, mineral-specific focus, and measurable economic impact under real operating conditions.

The biological toolkit

From microbes to plants

Over the past decades, AI and data analytics, as well as bioengineering tools and CRISPR, have evolved substantially. These advances provide the mining industry with several innovative technology approaches to address scarcity and supply gaps by unlocking low-grade resources in an economically viable and more sustainable way.

Phytomining

How plants are becoming miners

Phytomining serves as a compelling example of a bio-based approach in mining, leveraging the well-documented ability of certain plant species to naturally accumulate metals in their biomass when grown on metal-rich soils. These natural metal "hyperaccumulators" have been studied for decades, offering a dual opportunity to rehabilitate metal-contaminated land while biologically concentrating valuable resources in plant biomass for downstream recovery.

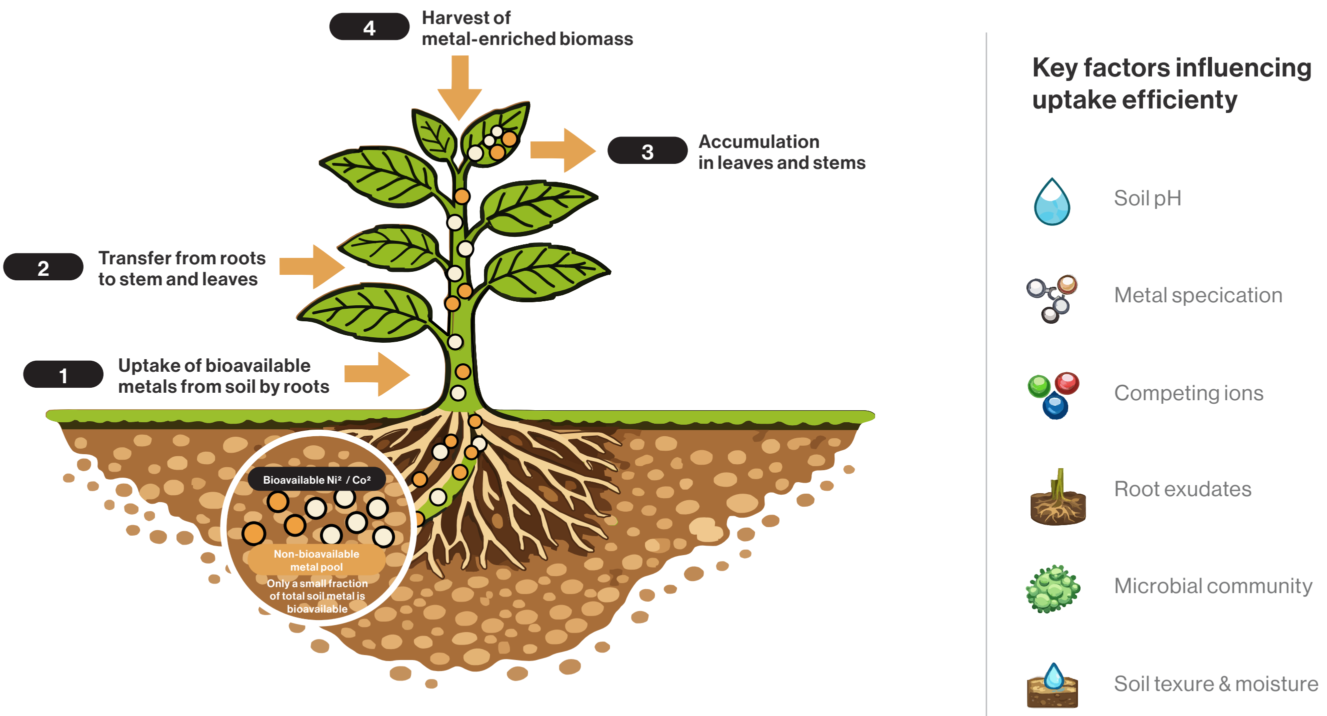
Scientific recognition of this phenomenon emerged in the 1970s with the work of researchers such as Jaffré, Brooks, and Reeves, who identified metal-hyperaccumulator plant species across regions including New Caledonia, the Mediterranean, and North America (Kikis et al., 2024).

Phytomining research activity accelerated in the 2010s, driven by critical-mineral supply concerns and environmental constraints on conventional mining. EU-backed programs in Albania have demonstrated repeatable nickel recovery, and research efforts are expanding in South Africa.

More recently, early signs of commercial translation have emerged. In 2023, global stainless-steel producer Aperam launched the "Botanickel" joint venture with French startup Econick to integrate nickel phytomining into a low-impact, circular steel supply chain (Aperam & Econick, 2023). In parallel, venture-backed companies such as Genomines are advancing from pilot programs toward expanded field trials to meet growing demand for nickel sourced through phytomining.

As multiple efforts approach early commercial-scale deployment, the coming years could represent an economic inflection point for phytomining as a novel pathway for sourcing critical metals.

Phytomining process: biological uptake and concentration of metals from metalliferous soils



Schematic illustration of phytomining, showing uptake of bioavailable metal ions from soil, translocation through plant tissues, accumulation in above-ground biomass, and harvest of metal-enriched plant material.

What is Phytomining?

Phytomining exploits the ability of hyperaccumulator plants to take up metals from the bioavailable fraction of soil and concentrate the metal in above-ground biomass (leaves and stems), which can subsequently be harvested. These plant species are typically associated with naturally occurring ultramafic and serpentine soils, which originate from metal-rich bedrock and contain elevated concentrations of elements such as nickel, cobalt, and chromium—often at levels an order of magnitude higher than typical agricultural soils. These soils are chemically hostile to most vegetation due to high metal toxicity and low nutrient availability, resulting in sparse plant communities dominated by a small number of adapted species.

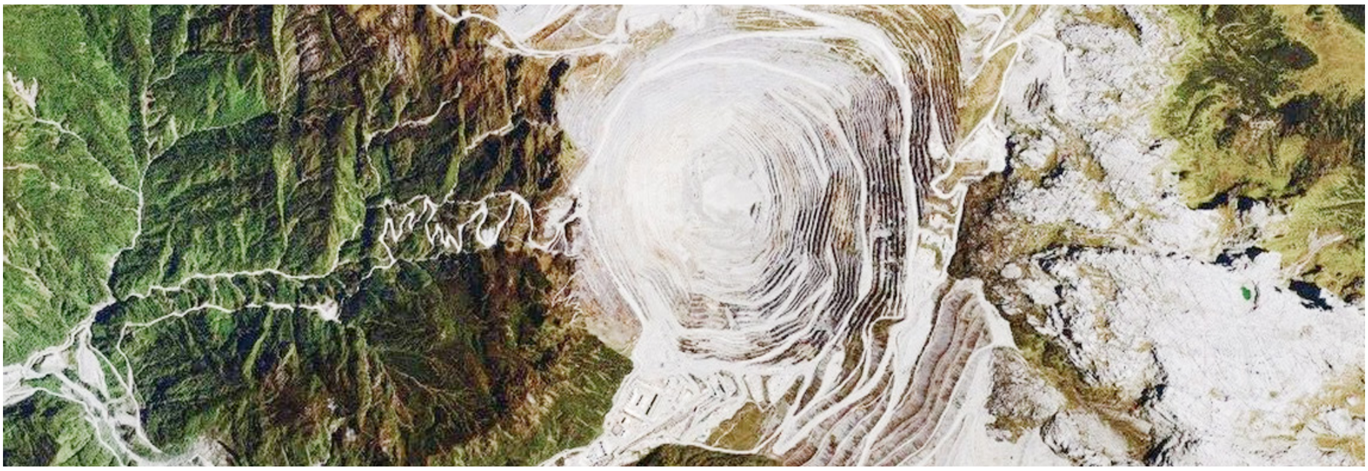
The phytomining process begins with the uptake of soluble metal ions by plant roots from surrounding soil, followed by translocation through the plant's vascular system to leaves and stems, and intracellular sequestration in compartments such as vacuoles or epidermal tissues to avoid phytotoxicity. Typically, only a small fraction of total soil metal is accessible for plant uptake. Uptake efficiency is governed by soil properties in the rhizosphere—the region surrounding the plant's root system—including pH, microbial community structure, and the presence of competing ions (Rascio & Navari-Izzo, 2011).

Many hyperaccumulators actively modify their rhizosphere through root secretions and interactions with soil microorganisms, increasing local metal solubility and bioavailability. Reeves et al. (2018) report hundreds of hyperaccumulator species, with more than 500 documented for nickel alone. Commonly studied systems include Alyssum (Odontarrhena) species in the Mediterranean and Phyllanthus species in Southeast Asia, where nickel concentrations of ~1–3 wt% in plant shoots have been repeatedly observed under favourable conditions (Nkrumah et al., 2016). These plants typically dominate metal-rich soils that are insufficiently concentrated for conventional mining yet too toxic for agricultural use, creating a potentially valuable deployment window for phytomining.

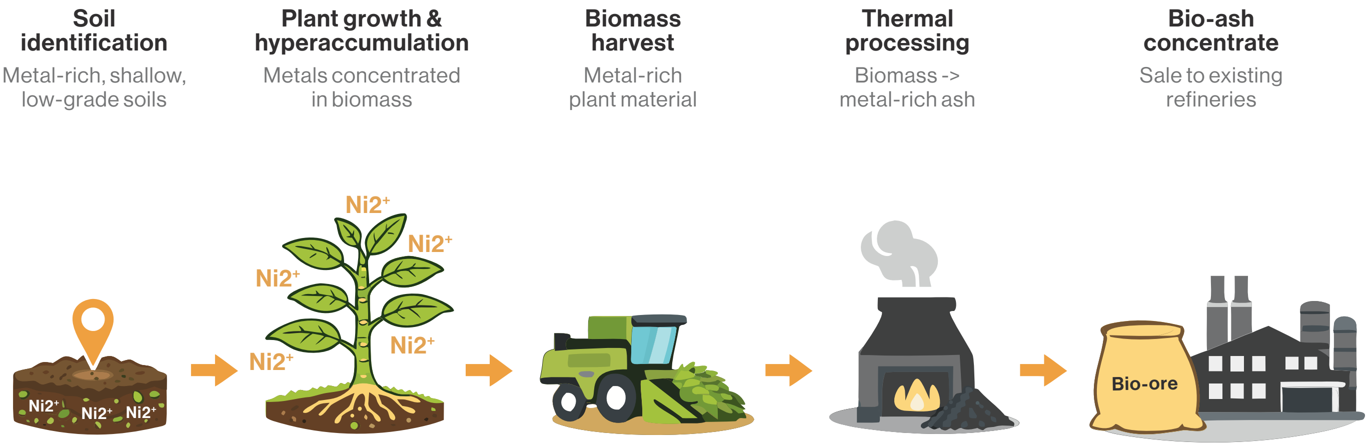
Suitable metals & value chain

Phytomining's near-term opportunity is not to replace large-scale mining, but to monetise shallow, distributed metal in ultramafic topsoils that fall below conventional cut-off grades and face high permitting barriers to excavation. Where land has limited alternative agricultural value, plant-based concentration can convert stranded surface resources into a refinery-compatible intermediate.

Nickel is the most mature and commercially relevant target to date. It plays a central role in stainless steel production and battery chemistries and faces growing supply risks as production shifts toward lateritic resources, which are capital-intensive, slow to develop, and associated with significant environmental impact (IEA, 2024). Greenfield nickel mining projects often require hundreds of millions of dollars in upfront capital and extended permit timelines. Beyond cost and ESG challenges, nickel supply chains are increasingly shaped by geopolitical concentration in mining and refining. In contrast, phytomining offers a lower-capital, more rapidly deployable complementary pathway for accessing shallow, low-grade nickel resources from ultramafic topsoils, supported by extensive research into nickel hyperaccumulator species.



Phytomining value chain: from metalliferous soil to metal concentrate



High-level overview of the phytomining value chain, illustrating the progression from metalliferous soil identification through plant-based metal concentration and delivery of a bio-ash concentrate into existing refining infrastructure.

Because ultramafic terrains are geographically widespread, phytomining could empower countries to develop a domestic nickel supply from surface soils. Cobalt represents a secondary opportunity, as it often co-occurs with nickel, although biological uptake competition introduces additional constraints.

From a commercial perspective, phytomining introduces a hybrid agricultural–industrial model. Production cycles resemble agricultural harvesting rather than conventional mine development, enabling faster deployment and lower upfront capital requirements. This can improve key operator metrics such as CAPEX intensity and time-to-first-production.

The phytomining value chain includes landowners or farmers operating on metal-rich soils, technology providers supplying optimised plant systems and agronomic protocols, processors converting harvested biomass into a metal-rich bio-ore, and refiners or end-market buyers. Rather than producing refined metal directly, phytomining generates a concentrated intermediate—typically in the form of ash or bio-ore following controlled thermal processing—that can be processed using conventional hydrometallurgical or pyrometallurgical routes (Vaughan et al., 2017).

Commercial viability depends on compatibility with existing refining infrastructure, with offtake value determined by metal concentration, impurity profile, logistics, and contract structure. Customers may include incumbent refiners, stainless steel producers, or downstream industrial users seeking to diversify supply or reduce environmental footprint.

Bioleaching

Leveraging the world's oldest miners

Microorganisms have mediated mineral transformations for billions of years, long before industrial mining existed. Certain microorganisms derive metabolic energy from redox reactions involving metals and sulphur compounds—a capability that, in mining-relevant settings, catalyses the oxidation of sulphide minerals. Through this process, insoluble metal compounds are converted into soluble ions that can be recovered through leaching and downstream processing. Central to this mechanism is the biological regeneration of ferric iron and sulphuric acid, which sustains continuous mineral dissolution while reducing the need for externally supplied chemical reagents (Jones & Santini, 2023).

Early forms of biomining predate modern industry by millennia. Historical records suggest that, as early as circa 700 BC in China (Qiu et al., 2023), copper was extracted from sulphide ores using acidic solutions generated by naturally occurring microbial oxidation. For much of the industrial era, however, such approaches remained constrained by slow kinetics and limited controllability (Dash, 2025). Advances in genomics, microbial community design, and process monitoring have since improved these limitations, enabling the use of engineered or selectively enriched microbial consortia tailored to specific ores and operating conditions.

For mining operators today, bioleaching is increasingly relevant as a process-intensification tool rather than a replacement technology. It enables the economic processing of lower-grade and more complex ores while reducing reagent consumption and energy requirements relative to pressure oxidation or roasting. As a result, microbial approaches are moving upstream in the mine lifecycle—from remediation and tailings treatment to active extraction and in situ recovery.

Industry adoption has accelerated in parallel with these technical improvements. Global mining incumbents are increasingly testing and deploying bio-based extraction technologies at scale. For example, Rio Tinto's Nuton bioleaching system has produced the first copper cathodes from primary sulphide ores after decades of research, demonstrating recoveries of up to ~85% on difficult ore types (Rio Tinto, 2025).

Beyond mining operators, downstream industrial players are also beginning to engage with biologically enabled extraction pathways, particularly as demand from data centre infrastructure and AI-driven computing intensifies pressure on copper supply. Companies operating large-scale data centres are increasingly exposed to the cost and carbon intensity of copper inputs, making access to more resilient, lower-impact supply strategically relevant (McKinsey, 2025). This is reflected in long-term offtake arrangements for bioleached copper, including those involving Amazon Web Services (AWS), as part of broader efforts to secure more transparent and lower-carbon supply chains (Rio Tinto, 2026).

Together, these developments indicate that microbial approaches are moving beyond experimentation toward strategic planning by both producers and large industrial consumers.

Suitable metals & value chain

Bioleaching is particularly well suited to mining contexts where mineral chemistry provides a natural energetic pathway for biological oxidation or reduction. Its applicability is therefore closely linked to ore mineralogy and processing route, rather than to a specific metal alone. The strongest use cases are found in sulphide-bearing and chemically complex ores, where conventional extraction methods are constrained by energy intensity, reagent consumption, or cost (Vera et al., 2022).

Copper remains the most established application. Microbial systems are widely used in heap leaching of low-grade secondary sulphides and, increasingly, in the treatment of primary sulphide ores that are uneconomic to process via smelting. Beyond active extraction, bio-assisted leaching has also been applied to legacy waste dumps and tailings, extending the productive life of existing assets.

For nickel and cobalt, microbial approaches are gaining relevance as ore grades decline and lateritic or mixed de-

posits become more prominent (Vera et al., 2022). In these settings, bioleaching can support leaching and pretreatment by enhancing metal solubilisation under milder conditions, reducing reliance on high-pressure acid leaching or energy-intensive thermal processes.
In gold mining, bioleaching is primarily used as a pre-treatment technology. Bio-oxidation of refractory sulphide minerals such as pyrite and arsenopyrite enables the liberation of encapsulated gold prior to cyanidation. This biological step increasingly replaces pressure oxidation and roasting, particularly where capital expenditure, emissions, or permitting constraints limit conventional options.

Engineered precision

Proteins and fungi as extraction tools

Protein engineering: Biological selectivity for metal separation

Proteins can bind metal ions with high selectivity through defined amino acid binding sites (Pothuraju & Karanth, 2022). This principle can be leveraged in mining and refining by engineering proteins that preferentially capture target metals from complex process solutions.

When immobilised on beads, membranes, or packed columns, engineered proteins function as selective sorbents, removing specific ions from leachates, brines, or recycle streams. These systems can be regenerated through controlled changes in pH, salinity, or temperature (Dong et al., 2021). Compared to conventional solvent extraction or precipitation-based methods, protein-based systems can reduce co-extraction of impurities and lower downstream reagent demand.

This approach is particularly relevant in refining and hydrometallurgy, where separation steps often represent a major cost and operational bottleneck (Dong et al., 2021). Promising applications include selective recovery of lithium from brines, targeted capture of valuable metals from pregnant leach solutions, and removal of impurities such as magnesium, manganese, or calcium.

Historically, biosorption approaches were limited by insufficient stability under harsh process conditions and poor durability over repeated regeneration cycles (Dong, Z., et al., 2021). Recent progress in protein engineering and screening methods have significantly improved the robustness of these systems, enabling protein sorbents that remain functional in industrial environments.

Overall, protein-based separations represent an emerging biomining pathway with strong strategic relevance. Rather than replacing entire flowsheets, these systems can be integrated as modular “drop-in” units to improve selectivity, reduce chemical intensity, and enable more efficient processing of lower-grade or complex feedstocks.

Fungi-related bioremediation

Fungi are increasingly being explored as tools for biomining and mine remediation, particularly for their strong metal interactions and their ability to support ecosystem recovery in degraded environments. Mycorrhizal fungi, which form symbiotic relationships with plant roots, are well established in mine rehabilitation contexts (Moura, M.A. de, et al., 2022). By extending root access to nutrients and water, they enhance plant establishment on disturbed substrates and improve tolerance to metal stress.

Beyond plant support, fungi can also directly influence metal mobility. Fungal biomass can bind heavy metals through adsorption and bioaccumulation, while fungal metabolites can precipitate, immobilise, or sequester metals in more stable forms. These properties make fungi relevant for both ecological restoration and long-term stabilisation of contaminated materials.

In practice, fungal deployment is typically part of integrated mine closure and rehabilitation strategies (Moura, M.A. de, et al., 2022). Rather than replacing physical containment or chemical treatment, fungal systems complement them. Common approaches include fungal inoculation combined with revegetation and soil amendments to stabilise tailings and waste-rock surfaces, reduce erosion and dust generation, and limit metal leaching over time. In this context, fungal networks can accelerate the development of persistent ground cover, which is often a critical bottleneck in long-term reclamation success. Despite strong mechanistic potential, large-scale deployment remains constrained by heterogeneity, local geochemistry, and climatic variability. Fungal establishment can be slow or inconsistent (Moura, M.A. de, et al., 2022), and maintaining biological activity across large mine footprints is operationally challenging. As a result, fungi are currently used primarily as supporting tools rather than standalone solutions.

Commercial delivery models may help address these constraints. For example, the UK-based startup Rhizocore Technologies has developed locally adapted mycorrhizal fungi for repeatable field deployment in large-scale tree planting. Such productised inoculation approaches could become relevant for reforestation-style mine closure programs, where improving early-stage plant survival can accelerate ecosystem recovery.

From lab to field

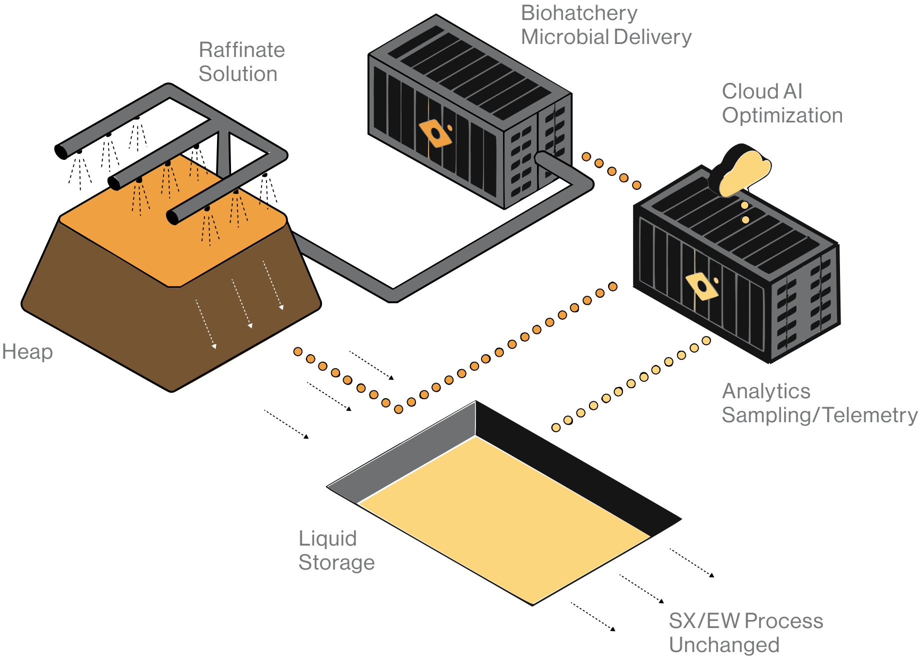
The emerging ecosystem

Although this field remains nascent, several promising players have emerged. In this section, we highlight two more advanced innovators disrupting the copper and nickel supply chains.

endolith

Endolith illustrates how microbial systems can enable a transition from conventional bioleaching to an integrated, operational technology for modern mining. The company applies microbial genomics alongside cloud-based monitoring and control systems to improve metal recovery from low-grade and complex ores, while reducing reliance on industrial chemical reagents. Its core premise is not to replace existing mining processes, but to embed biology directly into them—transforming microbial activity into a controllable, actively managed component of the extraction workflow rather than a passive background condition.

Endolith's biological intelligence platform seamlessly integrates with copper mines



Endolith has demonstrated copper recovery uplifts of approximately

1.7–1.9×

on low-grade sulphide ores, validated through column testing with partners including BHP.

Operationally, Endolith's approach is structured as a closed-loop system integrated into conventional leaching infrastructure. The process begins with biodiagnostics, in which genomic and chemical analyses of ore, raffinate, and process fluids establish a site-specific baseline for microbial and geochemical conditions. Tailored microbial consortia are then deployed into the leach system to generate biolixiviants in situ—biologically produced leaching agents that supplement or partially replace industrial acids. Continuous, real-time monitoring enables dynamic adjustment of microbial populations and operating conditions throughout the heap life, transforming bioleaching from a static treatment into an actively managed closed-loop process.

Roughly 70% of remaining global copper deposits are classified as low grade, meaning that future supply must increasingly be extracted from ore bodies with low metal content relative to the volume of material processed. Many deposits contain less than 0.5% copper by mass, or fewer than 5 kg of copper per tonne of ore, increasing energy use, reagent demand, and environmental footprint per unit of metal produced. Under these conditions, conventional heap leaching and bioleaching typically achieve recovery rates of ~20–40%, depending on ore type and operating conditions, limiting economic viability as cost and ESG pressures intensify.

With active commercial deployment underway with Tier-1 mining operators, Endolith has demonstrated copper recovery uplifts of approximately 1.7–1.9x on low-grade sulphide ores, validated through column testing with partners including BHP. At the scale of modern mining operations, such improvements can shift cutoff grades, extend asset life, and materially change project economics, unlocking new value from resources that would otherwise remain uneconomic.

Endolith points to a broader shift in how mining systems may be designed and optimised. Rather than treating leaching performance as a fixed outcome of ore chemistry and infrastructure, microbial inoculation introduces a dynamic layer that can be continuously adjusted over time. This reframes extraction efficiency from a one-time design parameter into an ongoing operational lever. As mining portfolios increasingly rely on marginal, complex, and environmentally constrained resources, such adaptive biological systems offer a promising new path for the industry: extending the economic life of existing assets, improving resilience under tightening regulatory and cost pressures, and enabling incremental supply growth without relying on new mines or major infrastructure build-out.

GENOMINES

Genomines employs a plant-based metal extraction method—phytoextraction (phytomining)—to extract nickel from soils unsuitable for conventional mining or agriculture, addressing constraints in global nickel supply. Its core technology leverages proprietary hyperaccumulator plants and selected consortia of endemic soil microbes to enhance metal uptake and concentration in plant biomass.

This system is complemented by proprietary land exploration tools and standard agricultural practices to produce intermediate materials that integrate into the nickel value chain and can be processed using existing refining infrastructure. At scale, phytoextraction has the potential to provide a more distributed and lower-impact source of nickel.

The process begins with global land screening using a proprietary digital tool to identify sites with suitable climatic conditions and ultramafic soil characteristics. This is followed by surface-level soil exploration to delineate areas with suitable nickel concentrations, typically between 0.2%–1.5%. Land is then prepared for cultivation of selected hyperaccumulator plants. As these plants are sterile, they are first propagated in vitro in local nurseries prior to field planting.

During growth, the plants accumulate nickel in above-ground biomass. Genomines' technology is designed to increase both biomass yield and metal concentration relative to naturally occurring hyperaccumulators, while remaining compatible with standard agricultural practices. Following harvest, the biomass is thermally processed to produce a nickel-rich bioconcentrate, which is then sold into established refining pathways to produce products such as mixed hydroxide precipitate or nickel sulphate.

The urgent need for phytoextraction is highlighted by structural changes in the nickel supply landscape. A growing share of global nickel production is shifting toward lower-grade, more environmentally intensive laterite deposits, while demand from batteries and electrification continues to rise. Conventional nickel mining is capital-intensive, slow to permit, and associated with significant environmental impact. Furthermore, supply and refining are increasingly concentrated geographically, particularly in Indonesia.

Phytoextraction offers a complementary pathway by unlocking surface-level resources that are currently uneconomic for traditional extraction. In principle, this can expand the accessible resource base while reducing reliance on deep excavation, environment-degrading extraction, and long development timelines.

Genomines has demonstrated the technical feasibility of the full workflow across laboratory, greenhouse, and early field settings. These results indicate that plant enhancement and microbial treatments can increase both biomass growth and metal accumulation. The company has produced nickel-rich bioconcentrate and nickel sulphate validated by battery and refining partners, indicating compatibility with existing processing and end-use requirements. It is now developing its first larger, multi-season field pilot to validate performance, reproducibility, and unit economics at scale.

Overall, Genomines represents an emerging class of biologically enabled extraction systems that combine plant biology, agronomy, and conventional metallurgical infrastructure into a single operational model. If validated at scale, such systems could substantially diversify the geographic supply and reduce the environmental impact of primary metal production.

A scalable end-to-end phytoextraction system: From land selection, cultivation, thermal processing to nickel concentrate

Genomines develops projects with genetically enhanced plants to extract and process nickel concentrate.

Bioengineering and microbiology

- Secure suitable & uneconomic land for mining
- Run the site with strict standard operating procedures (SOPs)
- Implement monitoring & compliance from day one

Exploration and land securing

- Deploy genetically engineered hyperaccumulators[1]
- Use sterile plant material
- Operate under strict biosafety and traceability protocols

Tailored agriculture and harvesting

- Apply tailored agricultural protocols to maximize biomass and uptake
- Implement scalable operational processes
- Harvest and manage logistics

Perennial crops: 2 harvests/year, productive for 10+ years

Biomass to nickel-rich concentrate processing

- Convert into a nickel-bearing concentrate
- Product fitting existing industrial processes
- Rotary kiln for consistent output

Note: 1) Hyperaccumulator plants capable of naturally absorbing metals through their roots and storing them in their tissues.

Overview of startups in biomining

Disclaimer: The categorisation of companies by maturity stage and technology type is based on publicly available information, company materials, and third-party sources. As many of these technologies are evolving rapidly, and as companies may operate across multiple modalities, this classification should be viewed as directional rather than definitive. We recognise that individual companies may assess their own maturity or positioning differently, and the intent is not to rank or evaluate specific firms, but to provide a structured overview of an emerging and dynamic landscape.

Biomining startups by maturity and technology

Maturity/ Technology	Lab validated (Mechanism & recovery on samples)	Pilot validated (Scaled reactor/heap/ column real feedstocks)	Mine/field validated (Site trials operational conditions)	Commercial deployment (Recurring operations/ revenues)
Phytomining	Rare Flora	GENOMINES		
Organismal mining	ekolive BRAINBiotech	1849BIO mint VIRIDIAN BIOMETALS AlkaLi LABS allonnia blueplanet.	endolith novonesis	nuton A Rio Tinto venture
Protein-based extraction	GIRAFFE BIO MAGMATIC	AETHER BIOMETALLICA SusPhos	MAVERICK X BioM BioMetallum	
Fungi-related biomining	RHIZOCORE TECHNOLOGIES			

From the landscape mapping so far, bioleaching and microbial optimisation appear increasingly crowded, whereas a clearer white space is emerging in biological selectivity and separation, particularly protein- and enzyme-enabled extraction and bio-inspired binders. These approaches can improve selectivity, reduce chemical intensity, and integrate into hybrid flowsheets (bio + hydrometallurgical/ electrochemical). This area remains underrepresented relative to the scale of the need and may represent an attractive investment opportunity, provided that economics and stability challenges can be effectively de-risked.

Detailed overview of biomining funding landscape

Company	Description	Geography	Latest financing round	Investors
Endolith	Adaptive microbial systems for copper recovery from existing heap leach operations.	Colorado, USA	Series A $16.5M in 2025	Squadra Ventures, Draper Associates, Collaborative Fund, Overture Climate Fund, Nucleus Capital
Genomines	Phytomining using plants to extract nickel from low-grade topsoil.	Paris, France	Series A $45M in 2025	Forbion BioEconomy & Engine Ventures (co-lead), DTCF, Wind Capital, Lowercarbon Capital, Hyundai, Entrepreneurs First
RI Rare Flora	Phytomining using plants to extract rare earths from soil.	California, USA	N/A	
Magmatic Bio	Protein-engineered refinement technology.	Vienna, Austria	Pre-seed in 2024	Founders Factory, Nucleus Capital
1849 Bio	Engineered microbes to extract copper from challenging ores like chalcopyrite.	San Francisco, California, USA	Seed in 2024	Y Combinator, FuturePlay, Monte Carlo Capital, Positive Ventures, Soma Capital
BacTech Environ-mental	Mine waste stream treatments for arsenic stabilization and reco-very of magnetite iron, ammonium sulphate and base metals (Ni; Cu; Co).	Toronto, Canada	Publicly traded	-
Giraffe Bio	AI-enabled cell-free metal extraction. High Throughput, microfluidic screening platform to test enzymes at scale (Li;Cu).	Buenos Aires, Argentina	Grant (funding round)	Start-Up Chile and AIR Capital.
BRAIN	Organismal bioleaching; containerized solution (BioXtractor) focused on Au, Ag, Pt, Pd, Co.	Hesse, Germany	Publicly traded	
Mint Innovation	Proprietary microbes to recover materials like Au, Cu, Ag, Sn, Pd, Co, Li, Ni from electronic waste and li-ion batteries.	Auckland, New Zealand	Series C NZD 60M in 2023	Liverpool Partners (Inspire Impact), K1W1, WNT Ventures

Company	Description	Geography	Latest financing round	Investors
Maverick Biometals	Enzymes to mine Li and rare earths.	Texas, USA	Seed $19M in 2025	Metaplanet, Soma Capital, Climate Capital
SusPhos	Bio-assisted phosphorus recovery from sewage sludge ash (urban mining).	Leeuwarden, The Netherlands	N/A	Innovatiefonds Noord-Holland, SHIFT Invest
Aether Biomachines	AI and high-throughput robotics to engineer proteins for critical material refinement.	Menlo Park, California, USA	Series A $15M in 2025 (previous Series A: $49M in August 2023)	Tribe Capital, Natural Capital, Henkel, Resilience Reserve, other
Biometallica	Engineered bacteria to recover platinum group metals (Pt, Pd, Rh).	Singapore, SGP	Seed (undisclosed sum) in 2023	IndieBio/SOSV
Viridian Biometals	Naturally occurring bacteria, enhanced with AI to extract and refine critical metals from ores.	Mill Valley, California, USA	N/A	Participated in two incubator programs (The Think & Act Differently Accelerator, Pasadena Bio)
Alkali Labs	Engineered microbes to recover Li from low-grade industrial waste (e.g. O&G-produced water). Focused on engineered microbe chassis with modified transport proteins and CRISPR-enhanced traits for metal uptake.	San Francisco, California, USA	Seed (undisclosed sum) in 2023	IndieBio, SOSV, Helene Ventures, Lexi Ventures
Allonnia	Natural & engineered microbes & proteins for bioremeditation (degrading 1,4-dioxane, PFAS) and critical mineral recovery.	Boston, Massachusetts, USA	Series A extension in 2025	Viking Global Investors, Bison Ventures, General Atlantic, BHP Ventures, Pivotal Capital Partners
Biometallum	Engineered bacteria for the extraction of Li from brine.	Buenos Aires, Argentina	2023 IndieBio accelerator program	IndieBio, SF500
Ekolive	Bioleaching (microbial weathering approach for release of minerals & secondary materials; used as soil & plant stimulants.	Kosice, Slovakia	€250k in 2023	MassChallenge Switzerland
Blue Planet Environmental Solutions	Landfill biomining/reclamation of legacy waste and recovery of high value materials.	Singapore HQ; operations across India, SEA	Series C III in 2025	Novo Holdings, IFU, Sysma Holdings Nomura, Mizuho Asia Partners

Company	Description	Geography	Latest financing round	Investors
Novonesis	Phosphate-solubilising microbes & enzymes.	Lyngby, Denmark	Growth-stage	Novo Nordisk Foundation
Nuton	Rio Tinto venture, is deploying nature-based bioleach technology set to unlock copper resources.	Melbourne, Australia	N/A	Rio Tinto

The biomining ecosystem remains at an early stage, but is clearly taking shape. The presence of publicly listed players (e.g., BacTech, BRAIN), corporate-backed ventures (e.g., Nuton by Rio Tinto), and venture-funded Series A–C companies (e.g., Mint Innovation, Allonnia, Endolith, Aether) provides early validation that biological extraction and refinement are transitioning from research concepts toward commercial applications.

At the same time, the majority of companies remain at the laboratory or pilot-validation stage. Field-validated and commercially deployed operations are still limited, and scaling remains both capital-intensive and operationally complex. Significant additional investment, both financial and strategic, will be required to transition these technologies from proof-of-concept to routine commercial deployment under real mining conditions.

A clear pattern emerging in the landscape is focus. The most credible companies tend to concentrate on one mineral system (e.g., copper, lithium, rare earths, PGMs, phosphorus) and develop deep technical, geological, and techno-economic expertise within that vertical before expanding into broader pipelines. Given the site-specific nature of mining economics and the complexity of biological systems, this focus appears essential. Demonstrating repeatable performance on a defined mineral type, supported by operational mining data, is likely a prerequisite for successful scaling and subsequent diversification.

Importantly, the competitive dynamic is not purely startup-versus-startup. The largest unlock in this sector is likely to come from structured collaboration between mining operators and emerging innovators. Field validation under real operational conditions represents a key inflection point in value creation—not only for startups seeking scale, but also for miners aiming to unlock stranded resources, improve recovery rates, and strengthen sustainability performance.

Mining operators therefore hold significant leverage in shaping the trajectory of the industry. By enabling controlled in-field testing and forming long-term partnerships with promising technologies, they can accelerate validation cycles while maintaining operational oversight. For startups, such partnerships provide access to real feedstock, site data, and operational credibility that cannot be replicated in laboratory environments.

Overall, the competitive landscape reflects an industry in transition: early commercial signals are visible, capital is flowing, and technological diversity is high. However, widespread adoption will require continued investment, disciplined focus on specific mineral systems, and, above all, sustained collaboration between miners and biomining innovators. The companies most likely to succeed will combine biological differentiation with operational integration and strategic industry partnerships.

The road from lab to mine

Performance under real-world conditions remains a critical consideration, as ore variability and environmental factors can materially affect outcomes. Operations require continuous monitoring of parameters such as pH and redox potential to ensure consistent performance. Advances in process control, modelling, and microbial engineering are improving reliability at scale, but variability remains a key risk factor.

Economic viability is closely tied to site conditions and operational design. Factors such as reaction kinetics, infrastructure requirements, and local input costs influence project economics, as in conventional mining. While dedicated systems (e.g. heaps or bioreactors) may be required, biomining can reduce reliance on high-temperature processing and lower overall energy intensity. With appropriate site selection and robust techno-economic modelling, biomining has the potential to become a competitive, lower-impact extraction pathway under favourable conditions.

Robust monitoring and integration are therefore essential. Mining operators seeking to deploy biological solutions should invest in data analytics and monitoring capabilities. In addition, biomining processes must be embedded within existing mine flowsheets, including materials handling, irrigation systems, effluent treatment, and downstream recovery, introducing additional engineering complexity and operational risk.

Regulatory constraints also remain significant. Even for technologies positioned as lower-impact alternatives, permitting timelines are unlikely to be materially shortened in most jurisdictions. Mining projects continue to require extensive environmental and social impact assessments. The use of engineered organisms introduces additional complexity, particularly in regions such as Europe, where regulatory frameworks and public acceptance remain restrictive. Operators must demonstrate that biomining does not introduce new risks, such as uncontrolled acid generation, mobilisation of unwanted metals, or broader ecological impacts.

Finally, mining timelines influence the pace of adoption. The sector is inherently conservative, and technologies are subject to extensive validation due to the high cost of operational failure. Pilot projects must demonstrate performance across varying feedstock and environmental conditions. At the same time, permitting and development timelines—often 10–15 years from exploration to production—limit the speed at which new technologies can scale through greenfield assets. As a result, commercialisation is heavily dependent on partnerships with operators and alignment with the lifecycle of active mine portfolios. Innovators entering the space should account for these extended sales and validation cycles when planning capital requirements.

How to win in biomining

Biomining is emerging as a practical pathway to unlock additional metal supply without relying solely on new mine development. Rather than competing directly with traditional greenfield mining, biomining startups can redefine what is considered economically viable feedstock.

The most credible near-term opportunity lies in mine waste, tailings, and legacy dumps. These materials often contain economically meaningful residual metal concentrations but remain underutilised due to the cost and energy intensity of traditional recovery methods. Biomining offers a pathway to extract additional value while addressing environmental liabilities, strengthening both the economic and permitting case.

Beyond waste streams, biomining can expand the resource base by targeting ores that fall below conventional cut-off grades, are too energy-intensive for pyrometallurgical treatment, or are chemically complex and refractory. In doing so, it has the potential to reduce upfront capital requirements, lower energy consumption, and improve the economics of marginal deposits.

For biomining startups, capturing this opportunity requires far more than strong biological performance; it requires deep integration with the mining ecosystem. Success depends on understanding miners' operational realities, regulatory frameworks, cost structures, and scaling constraints.

The path to commercialisation is inherently staged:

- **Lab validation:** Demonstration of recovery mechanisms and microbial/protein performance
- **Bench/column testing:** Repeatability on representative ore samples
- **Pilot trials:** Scaled heaps or reactors under controlled field conditions
- **Site deployment:** Long-duration performance in operational environments
- **Commercial rollout:** Integration into the operator's flowsheet and economics

This progression makes collaboration with mining companies foundational. Partnerships provide access to real sites, feedstock, and operational data, enabling startups to validate performance and refine techno-economic analyses using credible site-specific inputs in real-world conditions. At the same time, they give operators early insight into performance, risks, and integration requirements.

Mining companies must also recognise structural differences between startups and incumbents. Startups operate under tighter capital constraints and shorter timelines to reach defined value inflection points (often 1–2 years until they need to secure fresh funding). Structured innovation programs—based on clear milestones, transparent commercial thresholds, and predefined scale requirements—are therefore critical to successful collaboration. When expectations are aligned early and testing pathways are clearly defined, partnerships can accelerate validation cycles while maintaining operational discipline and risk management.

Ultimately, the success of biomining will depend on close alignment with mining operators. The companies most likely to succeed will be those that build deep, strategic partnerships that leverage existing infrastructure, geological expertise, and operational capabilities to unlock new value streams that would otherwise remain untapped.

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Bruno Meireles de Sousa is an Operating Partner at Bidra Innovation Ventures. Bidra invests in founders that reinvent agriculture, industrials, and mining. Headquartered in the United States, we deploy capital globally, supporting early and growth-stage startups. The OCP Group, our sole Limited Partner, is a global leader in mining, industrial operations, and agriculture, with a 100-year track record of delivering critical inputs to feed the world. Its innovation ecosystem, built around the University Mohamed VI Polytechnic, shapes the future of applied research in Africa and trains the continent's next generation of builders and leaders.

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