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Mine-on-a-chip: megascale opportunities for microfluidics in critical materials and minerals recovery

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The rising supply gap for metal resources essential to energy, defense, and consumer technologies—the critical minerals and materials—poses one of the most pressing bottlenecks toward energy and national security. A suite of challenges ranging from resource definition to extraction and refining, however, undergird the economic feasibility and cradle-to-grave sustainability of these technologies. Myriad opportunities exist to leverage the unique advantages of microfluidics – low sample and reagent consumption, parallel processing, and rapid and low-cost testing – to understand and improve existing approaches for materials characterization, extraction, chemical analyses, reagent screening, separation. This perspective identifies key gaps and opportunities in securing the supply of minerals and materials critical to energy sustainability and aims to galvanize the lab on a chip (LoC) community in this crucial research.

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Minerals and their criticality to energy sustainability

Achieving the 2 °C climate target set in the Paris Agreement will require a ~10- to 100-fold growth in decarbonization technology deployment by mid-century.[1–4] Energy transition technologies such as wind, solar (photovoltaics and thermal), electric vehicles, hydrogen, and batteries, however, all rely critically on a set of metal elements (*e.g.*, lithium, cobalt, nickel, rare earth elements, and platinum group metals) for their basic functionality (Fig. 1).[5] Increasing electrification and decarbonization of the global energy economy, therefore, imposes demands on this collection of elements—the so-called "critical minerals and materials" as defined by the U.S. Geological Survey (USGS) and Department of Energy (DOE)—at unprecedented rates,[6] whose reliable and cost-effective availability are essential to economic security and energy sustainability.[6–8]

Rapid growth in the demand for critical materials and minerals, however, leaves key vulnerabilities in decarbonization efforts as supply gaps emerge. For example, the demand for Li, Ni, and Co is projected to increase between 20- and 40-fold by 2040 as a result of battery storage and electric vehicle adoption, yet supply growth from existing and planned mining operations, characterized by diminishing ore grades and long lead-times from discovery to first production (>16 years), will be slow to follow.[9] The issue is exacerbated by the geographical concentration of both resources and processing facilities, where trade dependencies effect price volatility and disrupt the economic feasibility of decarbonization technologies.[10] Current mining and processing practices are further weighed by their energy intensity and environmental emissions that challenge the economic feasibility of new production. While secondary streams such as waste recycling provide a pathway to reduce the demand for new ore extraction, they remain insufficient as a near-term substitute (insufficient end-of-life materials until 2040, when recycled Li, Ni, Co, and Cu from spent batteries can reduce primary supply by ~10%).[9,11] Continued mapping of new and unconventional critical mineral resources along with their economic and ecologically sound extraction and processing are therefore critical to ensuring a rapid and economically-viable energy transition.

This perspective calls on the lab on a chip (LoC) community to develop solutions that will help close the ever-growing gap in the critical mineral and materials supply chain. Expanding and securing the supply of critical minerals, from exploration to refining, will require extensive materials characterization, mechanistic elucidation of microscale fluid–mineral interactions, analyses, screening, and separation, all capabilities inherent to microfluidics. In the following, we provide a description of the critical minerals and materials, their uses, and criticality to energy sustainability along with a summary of their current extraction, processing, and the challenges that exist therein. We highlight recent advances that the LoC community has contributed in response to the need for securing the critical minerals supply chain, and

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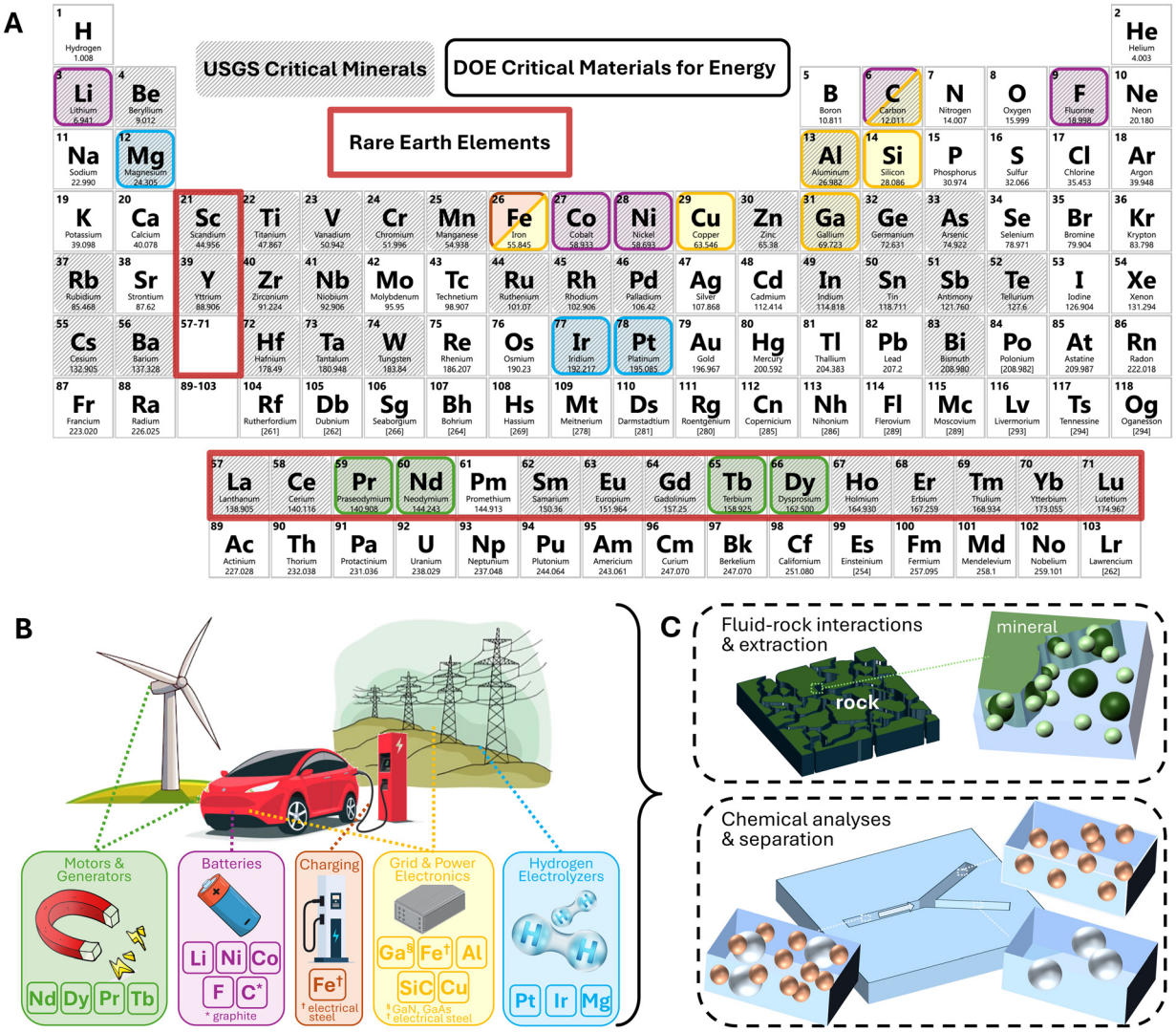

Fig. 1 Elements critical to energy sustainability, their uses, and opportunities for the lab on a chip community. (A) Critical materials and minerals highlighted on a periodic table. Critical minerals as defined by the USGS are denoted by diagonal hatching. Critical materials for energy (*i.e.*, DOE's electric eighteen) are colored according to their uses in B. The rare earth elements (*i.e.*, lanthanide series plus scandium and yttrium) are encircled in red. (B) The DOE's critical materials for energy related to their uses in motors and generators for electric vehicles and wind turbines, batteries, charging infrastructure, grid and power electronics, and the hydrogen economy. (C) Opportunities for innovation using lab on a chip techniques in chemical analyses, separation, purification, extraction, and elucidation of fluid–rock interactions.

outline a set of "mine-on-a-chip" opportunities for which microfluidics techniques are well suited.

Definition of critical materials and minerals

The Energy Act of 2020 defines *critical materials* as "any non-fuel mineral, element, substance, or material that... (i) has a high risk for supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies those that produce, transmit, store, and conserve energy" identified by the U.S. DOE. Similarly, *critical minerals* are defined in the Energy Act of 2020 as "any mineral, element, substance, or material designated as critical" by the U.S. Geological Survey.[12]

The 2023 DOE Critical Materials Assessment (CMA) identified 18 elements (*e.g.*, Li, Nd) and material composites (*e.g.*, silicon carbide, electrical steel) crucial to energy sustainability in the immediate and medium term (through 2035, Fig. 1A, colored, and B): aluminum (Al), cobalt (Co), copper (Cu), dysprosium (Dy), electrical steel (Si–Fe), fluorine (F), gallium (Ga), iridium (Ir), lithium (Li), magnesium (Mg), natural graphite (C), neodymium (Nd), nickel (Ni), platinum (Pt), praseodymium (Pr), terbium (Tb), silicon (Si), and silicon carbide (SiC).[13] These 18 materials, the "electric eighteen", are of particular criticality due to their importance to energy and vulnerability to supply risk (Fig. 2). In the CMA, the importance of a material to energy is defined by the market use of a material in existing and future energy technologies as well its capacity for substitution.[13] Supply risk is evaluated by the

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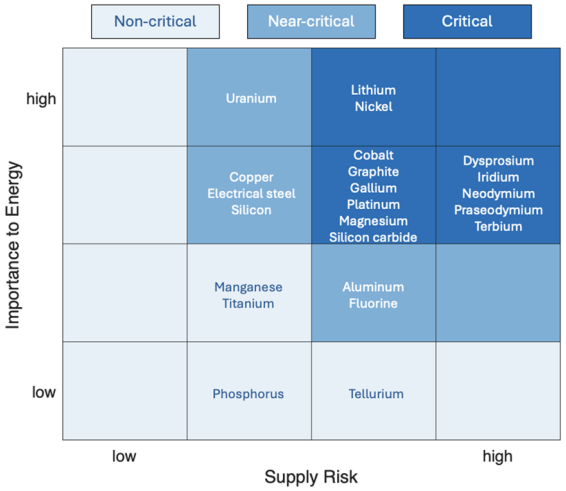

Fig. 2 Set of materials that are critical to the energy sector in the immediate and medium term (2025 to 2035) according to the U.S. Department of Energy 2023 critical minerals assessment.[13]

capacity for global supply to meet demand based on technology growth trajectories for deployment scenarios,[14,15] competition from non-energy sectors, geographical market concentration, co-dependence of precious minor elements on lower-value products, and social and political factors, including regulatory, labor, and export restrictions.[13]

The 2022 USGS list of *critical minerals* comprises 50 elements and crystallographic compounds (*e.g.*, barite, fluorspar) important to economic or national security (Fig. 1A, hatched): aluminum (Al), antimony (Sb), arsenic (As), barite ($BaSO_4$), beryllium (Be), bismuth (Bi), cerium (Ce), cesium (Cs), chromium (Cr), cobalt (Co), dysprosium (Dy), erbium (Er), europium (Eu), fluorspar (CaF_2), gadolinium (Gd), gallium (Ga), germanium (Ge), graphite (C), hafnium (Hf), holmium (Ho), indium (In), iridium (Ir), lanthanum (La), lithium (Li), lutetium (Lu), magnesium (Mg), manganese (Mn), neodymium (Nd), nickel (Ni), niobium (Nb), palladium (Pd), platinum (Pt), praseodymium (Pr), rhodium (Rh), rubidium (Rb), ruthenium (Ru), samarium (Sm), scandium (Sc), tantalum (Ta), tellurium (Te), terbium (Tb), thulium (Th), tin (Sn), titanium (Ti), tungsten (W), vanadium (V), ytterbium (Yb), yttrium (Y), zinc (Zn), and zirconium (Zr). Although the broader list of 50 minerals identified by the USGS are essential to the economic and national security of the U.S.,[16] this perspective will focus on the DOE's list of energy-critical materials (*i.e.*, the "electric eighteen"). Importantly, we note that the criticality of elements to the energy economy is fluid and evolves with developments in supply and technology such that currently near-critical and non-critical materials may become critical in time.

Rising demand for critical materials

For the electric eighteen, material criticality is driven primarily by surges in recent and projected use of electric vehicles, battery storage, hydrogen electrolyzers, efficient lighting, power electronics, and grid infrastructure.[13] Adoption of electric vehicles rose ~15-fold from 2015 to 2022 and is projected to grow ~30-fold by 2040[9,13] These unprecedented rates of EV technology adoption drive an increasing supply gap in the materials critical to battery storage (Li, Co, and natural graphite, Fig. 3), high-grade permanent magnets used in electric motors (Nd, Dy, Pr, and Tb, Fig. 3), motor and charging infrastructure (electrical steel), and power electronics (SiC and GaN). Specifically, lithium-ion batteries leverage the small size and large charge density of lithium, suitable for reversible intercalation in electrodes, to provide energy-dense rechargeable storage. Cobalt, nickel, and graphite electrodes are used commonly to maximize the energy storage density of Li-ion batteries. Consumption of battery electrolytes such as lithium hexafluorophosphate and polyvinylidene fluoride will increase accordingly, raising demand for fluorine. Although next-generation battery chemistries targeting Earth-abundant materials may reduce the material intensity and criticality of lithium and cobalt, market momentum for current low-cost technologies remains. Together with grid-scale battery storage, the demand for lithium by the EV sector is anticipated to increase ~40× by 2040, double the supply projection from existing mines and planned projects, with accompanying demand growth for graphite, cobalt, and nickel expected at ~20- to 25-fold.

A second set of minerals essential to the function of electric vehicles are the rare earth elements. Specifically, EVs rely on permanent magnets in their motors to convert between electrical and mechanical energy.[17] Demand for lightweight, compact, and high-grade magnets—the most economic of which are neodymium-iron-boron (NdFeB) magnets—is a key factor driving the REEs toward criticality.[17–19] Here, the rare earth elements, including neodymium, dysprosium, praseodymium, and terbium, are leveraged for their large magnetic momentum, given by their unique electronic configurations where electrons partially occupy their 4f orbitals. The functional criticality of REEs in permanent magnets, therefore, ties their demand closely to the adoption of EVs, the sales of which increased ~35% year-on-year between 2023 and

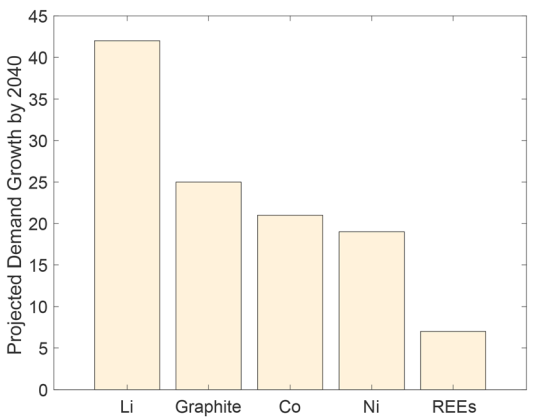

Fig. 3 Projected growth in demand for critical minerals used in batteries, electric vehicles, and wind turbines. Data from EIA report.[6]

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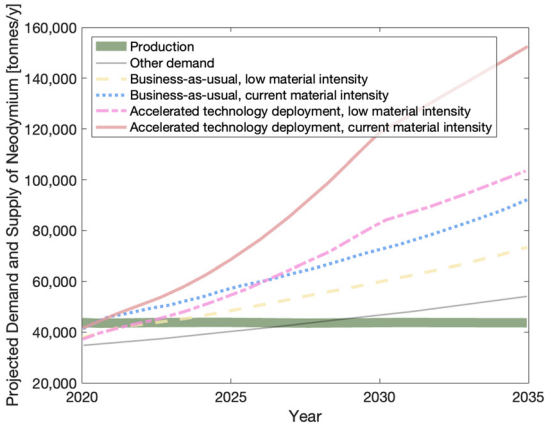

Fig. 4 Growing gap between global demand and production of neodymium. Four demand scenarios are considered here as a function of market penetration and material intensity of technology. Modified from the U.S. Department of Energy 2023 critical minerals assessment.[13]

2024.[20] While the development of REE-free magnets promises to reduce the criticality of REEs, their functionality relies on other critical minerals such as Pt, Ni, and Co.[21,22] Sustained growth in market share, even at business-as-usual rates, is expected to generate supply gaps in REEs that will undermine the economic feasibility of low-carbon energy technologies (Fig. 4).

Elsewhere, the growth in renewable electricity generation is also a key driver in mineral criticality. Off-shore wind capacity is anticipated to increase 5- to 7-fold by 2035,[23] increasing demand for rare earth magnets that are essential to the function of its generators. Dysprosium is particularly important for resisting demagnetization over long periods of performance.[17] Similarly, power production from solar photovoltaics grew 25% from 2022 to 2023,[24] causing stress to the supply of silicon semiconductor materials. Specifically, crystalline silicon (Si) remains the most widely used and cost-effective semiconductor material for photovoltaics, while newer solar cell arrays leverage gallium nitride (GaN) for its wide bandgap with low sensitivity to ionizing radiation.

To ensure grid security, power generation from intermittent energy resources (*e.g.*, wind or solar) drives the growth of grid-scale storage technologies. Battery storage is anticipated to grow ~40-fold by 2030,[13] with demand in Li, Ni, and graphite resources to follow. In addition to batteries, non-electric materials suitable for long-duration energy storage, such as hydrogen, will be required to compensate for daily and seasonal fluctuations. Growth in the production of green hydrogen (*i.e.*, H_2 reduced from water using a proton exchange membrane, PEM, and electrolyzers) will drive the demand for stable electrolytic catalysts. Here, platinum and iridium, members of the platinum group elements (PGEs), are critical to catalyzing water electrolysis.[13] Specifically, Pt and Ir show excellent chemical stability in extreme aqueous environments and catalyze oxygen- and hydrogen-evolving reactions during water electrolysis, respectively.[8] Magnesium, similarly, provides high energy density and excellent electrochemical properties that enable its application in next-generation battery and H_2 electrolyzer technology.

Lastly, to accommodate increased electrification, sustained growth in power electronics and in the grid market (~150% increase by 2032 (ref. 13)) will stress existing supplies of silicon carbide (SiC), gallium nitride (GaN) and arsenide (GaAs), electrical steel, copper, and aluminum. Major conductor elements, such as aluminum, copper, and electrical steel, provide critical function in the electrical infrastructure, from power lines to motors.

Overall, demand for the "electric eighteen" is projected to increase at unprecedented rates, the supply of which is critical to a sustainable and secure energy future. The global aggregate market value of lithium, nickel, cobalt, copper, graphite, and the rare earth elements was ~US$325 billion in 2023 and is expected to increase to ~US$770 billion by 2040.[14] Yet, key vulnerabilities exist in their supply as a result of the heterogeneity of natural resources, their energy- and emissions-intensive production, and potential geopolitical barriers. In the following, we discuss these challenges and outline opportunities for the LoC community to participate.

The problem with critical materials supply

Reliable supply of the critical materials above provides the necessary foundation for a timely and cost-feasible energy transition. Gaps in supply create market vulnerabilities that undermine the pace, price, and scale at which decarbonization technology can be deployed. Key stressors to the global supply of minerals include the geographical concentration of resources and processing capabilities, timescales associated with mine development, declining resource quality, and concerns over the environmental and social implications of mining practices.[9] Here, we discuss the challenges associated with sourcing of critical minerals and outline prospects for how microfluidics can help to broaden the supply through unconventional resource characterization and materials extraction and separation.

Mineral resources: occurrence and alternatives

Global occurrence of energy-critical minerals is nonuniform, with mining operations concentrated geographically in a small number of countries. As an example, we highlight here the geographic concentration of both the resource base and processing capabilities of the rare earth elements.

Despite what their name suggests, the rare earth elements (REEs) occur ubiquitously throughout the Earth's crust. Concentrated deposits of economic value, however, are scarce. Current economic accumulations of REEs are hosted in and mined primarily from magmatic deposits and weathered clays in China (Fig. 5, ~50 and 70% of global reserves and production in 2024, respectively).[17,18,25,26] While the REEs typically occur together, mineral ores such carbonatite (>50% calcite and/or dolomite), monazite ((REE,Th)PO_4) and

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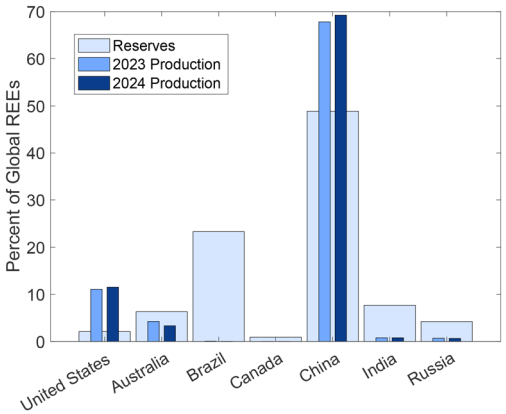

Fig. 5 Concentration of global occurrence and production capacity of REEs in a few countries. Resources and extraction are dominated by China. Nonuniform geographic distribution of supply presents vulnerabilities in the reliability and availability of raw material resources needed for sustainable energy technologies. Data from USGS minerals commodities report 2025.[10]

apatite ($(Ca,REE)_5(PO_4)_3(F,Cl,OH)$) tend to be enriched in light REEs (LREEs, from La to Eu). Meanwhile, heavy REEs (HREEs, from Gd to Lu, and Y, Sc) accumulate at elevated concentrations in weathered clay systems.

The principal commercial source of the LREEs is carbonatitic ore, an igneous rock crystallized from CO_2-rich fluids.[27] Typically, carbonatitic deposits are enriched in light REEs with few HREEs (*e.g.*, Dy and Tb) as a result of fractional crystallization.[27–30] Here, enrichment is enabled *via* hydrothermal convection in continental rift settings, where REEs in deep mantle melts whose large ionic radii are incompatible with the crystal lattices of most rock-forming minerals are excluded, remain in solution, and precipitate as REE-enriched phases.[17,29,30] Specifically, the nuclear charges of the REEs are weakly shielded by their 4f electrons, and result in decreasing ionic radii with atomic number (*i.e.*, the so-called "lanthanide contraction"). As a result, the smaller HREE cations are incorporated more readily in rock-forming minerals in the Earth's crust, while the larger LHREEs remain in solution.[27,28,31] The higher solubility of LHREEs in hydrothermal fluids leads ultimately to the precipitation of mineral ores that are enriched in LREEs such as carbonatites. Of the four major carbonatitic mines in operation, three are in China – Bayan Obo (~4 to 6 wt% rare earth oxides, REOs), Maoniuping (~2 wt% REOs), and Dalucao (~2 wt% REOs) – and one in the U.S. (Mountain Pass, California, ~8 wt% REOs).[17,32]

The HREEs including Dy and Tb, on the other hand, are extracted primarily from the weathered ion-adsorption clays of Southern China.[33–38] Primary mineral phases that hold elevated concentrations of REEs include kaolinite where REEs are adsorbed weakly on basal surfaces.[39] Enrichment of HREEs in clays follows the supergene process. Specifically, in the warm and humid subtropics, REEs held in granitic and tuff minerals are released *via* weathering and carried by meteoric water into the clays below (*i.e.*, supergene enrichment).[33–35] Heavy rainfall in temperate climates further enhances supergene enrichment by removing the overlying REE-depleted material and enabling continuous REE enrichment in the clays (~500 to 2000 ppm).[39–43] Although REE concentrations in clay deposits are low compared to those of primary igneous ores, commercial mining from clays is feasible owing to their HREE concentration, high surface area to volume ratio, ease of mining, and weak REE attachment.[39,44–48]

Beyond REEs, other energy-critical material resources are likewise concentrated geographically. Cobalt deposits are mined principally in the Democratic Republic of Congo (DRC), which, as of 2024, held ~55% of global reserves and contributed ~76% of production (Fig. 6). For lithium, over 50% of global reserves and production in 2024 were controlled by Chile and China. The challenges with geographical concentration extend beyond those of resource heterogeneity and extractive operations; concentration of refining capabilities is similarly acute, with ~85 to 90% of all refined REEs and ~50 to 70% of lithium and cobalt on the market originating from China. The geographical concentration of raw mineral resources, their mining, and refining leads to global interdependencies on trade and policy and introduces key vulnerabilities in the price and reliability of the critical material resources needed for decarbonization.

Democratizing the supply of critical material resources relies on broadening the existing supplies to include unconventional and secondary resources such as lower-grade natural deposits,[49] industrial and mine wastes,[49–52] and end-of-life devices (*i.e.*, electronic wastes).[11] Legacy coal ash, for example, are fine particulate residues accumulated from centuries of coal combustion around the world that hold elevated concentrations of the REEs (up to 1500 ppm reported).[52–56] U.S. stockpiles of coal ash are estimated around ~5.3 gigatonnes (1.5×10^{12} kg)[52] and are collected primarily in unlined landfills and ponds that leak contaminants into local ecosystems.

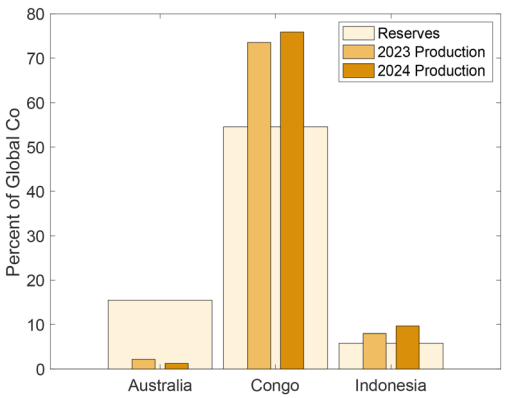

Fig. 6 Concentration of global REE occurrence and production capacity in a few countries. Resources and extraction are dominated by China. Nonuniform geographical distribution of supply presents vulnerabilities in the reliability and availability of raw material resources needed for sustainable energy technologies. Data from USGS minerals commodities report 2025.[10]

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Extracting REEs from these legacy waste piles hence provides an exciting horizon to valorize while remediating legacy ash simultaneously.[49]

Much remains unknown, however, about the physicochemical characteristics of these materials — often with high degrees of heterogeneity and complexity—and their conduciveness to mineral extraction. REE extraction from coal ash, for example, is complicated by regional variations in composition and inadequate descriptions of their material properties that limit current state-of-the-art recovery to only ~15%. As a result, coal ash is currently considered an abundant but non-economic resource. To leverage unconventional resources, deposit mapping and the development of economically-viable extraction approaches will require extensive sets of spatial and chemical analyses. Historically, material characterization of low-grade ore and industrial wastes has been sparse as a result of their low economic value. Here, to compensate for the lower resource grade of unconventional supplies, approaches that are inexpensive, rapid, and amenable to large sets of experiments (unique capabilities of microfluidics) will be particularly sought-after.

Extraction: economic and environmental costs

Additional vulnerabilities in meeting the ever-growing demand for critical materials are marked by the economic and environmental costs associated with mining, extraction, and processing. Myriad challenges exist, from the depletion of existing ore, diminishing ore quality, and lead-times for new mine developments, to the ecological impacts of mining and extraction, environmental emissions, and competition for strained resources (*e.g.*, water). Technology growth has driven the mining of high-grade ore, where costs associated with extraction and processing are minimal. Resource exploitation, however, has depleted easy-to-access and easy-to-process deposits, leading to the growing importance of lower-grade accumulations. Copper ore grades in Chile, for example, have decreased by ~30% over the past 15 years.[9] Mining, extraction, and processing of deposits with low CMs concentrations, however, are associated with higher energy and economic costs as well as environmental emissions (CO_2, tailing waste, spent reagents, *etc.*).

To compensate for the growing gap between demand and declining ore quality, new mines will need to be developed. On average, mining projects require ~16 years from discovery to first production.[57] These timescales far exceed those necessary to sustain the energy transition. Here, opportunities exist for leveraging unconventional and secondary resources such as mine and other industrial wastes as well as the co-production of critical minerals (*e.g.*, REEs) from existing mining operations.

Once mined, mineral ores undergo a series of processes to extract, separate, purify, and refine them into commercial products (*e.g.*, rare earth oxides and lithium carbonate).[58] Each step is energy- and reagent-intensive, and generate large volumes of waste that impact economic and ecological viability. Economic extraction of REEs from high-grade bastnäsite ore, for example, relies on high-temperature roasting (*e.g.*, 500 °C) to decompose the carbonate mineral as a means to minimize acid consumption.[59,60] On average, each tonne of REEs produced from these high-grade carbonatites generates ~8.5 kg of fluorine, 13 kg of flue dust, and 9600 to 12 000 m^3 of hydrofluoric acid (HF), sulfur dioxide (SO_2), and sulfuric acid (H_2SO_4) gas emissions, ~75 m^3 of acidic waste water, and ~1 tonne of radioactive waste residues (thorium, uranium, *etc.*).[61,62] Similarly, REE extraction from monazite emits 65.4 kg CO_2e/kg of greenhouse gases, and consumes ~11 170 kg kg^{-1} of water and ~917 MJ kg^{-1} of energy.[63] Water stress, particularly in arid regions (*e.g.*, Inner Mongolia), poses additional challenges to the sustainability of mining operations. Likewise, the production of heavy REEs from supergene clays *via* leaching of *in situ* ammonium sulfate ($(NH_4)_2SO_4$) emits ~258 to 408 kg CO_2e and consumes ~270 to 443 MJ primary energy per kg of mixed HREOs, all the while altering the local soil geochemistry.[64] Extraction processes that limit the ecological footprints of both open-pit LREE mining and *in situ* HREE leaching are sought urgently.

In addition to reducing the ecological footprint of CM extraction from conventional ores, securing CM supply will also require economic and environmental recovery from lower-grade unconventional resources. Secondary resources and wastes, such as coal ash, hold potential to expand REE production ~7- to 8-fold.[52] Current extraction approaches, however, are reagent- and energy-intensive and limit the market viability of the resource.[65] State-of-the-art processes include alkaline pre-digestion (used to dissolve the whole ash into water-soluble products) followed by acid dissolution of CM-bearing minerals. While the process enables REE extraction, recovery is typically limited (~15%).[66] Worse still, the approach consumes enormous volumes of reagents to dissolve the total ash matrix (99.9% of mass for ash with 1000 ppm REEs) and requires roasting at elevated temperature (~300 to 900 °C), both energy- and reagent-intensive processes.[56,67] To date, approaches that leverage waste and secondary sources of CMs remain economically nonviable.[49]

Many questions remain around the reaction pathways and kinetics, secondary processes, and reagent chemistry that are necessary to design effective and cost-efficient approaches for CMs extraction. Fundamental understanding of the geochemical characteristics of feedstock materials, including coupled reaction and mass transfer processes in the beneficiated media and the screening of reagents for high-yield extraction, are needed. Capabilities to visualize multiphase reagent transport through beneficiated ore and unconventional materials provide a means for direct observation of extraction processes in porous and/or granular resource beds. Fundamental geochemical interactions between reagents and the resource must be understood to engineer green chemistry approaches for accelerating CMs extraction. Similarly, processes to minimize and recycle reagent wastes are needed to reduce the ecological impacts and to increase the economic viability of alternative extraction approaches.

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Separation

Once the CMs have been extracted from feedstock material (ore, industrial wastes, *etc.*), they need to be separated and purified prior to market use. Typically, CMs occur together with secondary species that are co-extracted. Physicochemcial similarities between CMs and associated cations render their separation difficult.

In salar brines, for example, lithium (~100 to 1000 ppm) is commonly associated with major cations that are difficult to separate from (*e.g.*, ~10 wt% Na, K, Ca, and Mg).[68,69] Currently, the production of a relatively pure Li product (*e.g.*, >99% purity Li_2CO_3, LiOH) separates Li from secondary cations *via* a sequence of precipitative and fractionative processes that are slow (~24 months) and inefficient (~30 to 50% loss during evaporative precipitation).[70] Selectivity of Li from magnesium, for example, is particularly challenging due to the physicochemical similarities between the two hydrated species. Specifically, Li and Mg have similar hydrated ionic radii (3.8 Å for Li, 4.3 Å for Mg^{2+}).[71] Recent advances include the use of solvent extraction, sorbents (*e.g.*, aluminum-, titanium-, and manganese-based spinels), membranes, and electrodialysis to separate Li from dissolved Mg^{2+} but are challenged by costly reagents and energy requirements.[72] Favorably, the effectiveness and cost-feasibility of separation technologies improve with Li enrichment (*i.e.*, Li/Mg, Li/Na, Li/Ca, Li/K ratios). Processes that enrich Li in brines, therefore, will provide an important avenue toward the market feasibility of Li separation technologies. Similarly, solutions that allow the separation of Li from low-grade resources (*e.g.*, oil and gas produced waters)[73] are also needed to broaden the supply of Li.

Separation of REEs is challenging due to their natural co-occurrence, their association with more abundant major cations (*e.g.*, Ca, Al, or Fe), and their co-existence with radionuclides (up to ~20 wt% thorium and uranium oxides in monazite).[17,18] Physicochemical similarities between REEs, namely their trivalent charge and ionic radii, lead to their co-occurrence in nature.[74] Specifically, crystallization of principal rock-forming minerals (*e.g.*, silicates) favors the incorporation of cations with valences of 2 or 1 and excludes REE^{3+} cations, leading to the later formation of REE-enriched ore that contains the entire lanthanide series.[17] Purified individual rare earth metals or oxides production, therefore, requires selectivity based on subtle differences in ionic size and charge.

Approaches to separate the individual REEs include fractional crystallization (*i.e.*, selective precipitation), redox, ion exchange, and solvent extraction.[32,75–79] Fractional crystallization, for example, is used to precipitate the heavy REEs from ion-adsorption clays as oxalate salts.[80] Above very low pHs, rare earth oxalates precipitate readily while major cations (*e.g.*, alkalis and alkali earths) remain soluble.[80] Selectivity from transition metals and radionuclides, however, is limited by co-precipitation, while separation between the individual REEs requires many stages of precipitation and dissolution owing to the low solubility product and water solubility of REE salts.[80–82] As a result, selective precipitative processes consume extensive volumes of reagents that raise the economic and environmental costs of separation. Ligand-based approaches such as ion exchange and solvent extraction face similar challenges in the competition between REEs and secondary species for binding sites and its reagent use.

Techniques to purify and separate critical minerals from their associated species are needed to produce market-ready CM streams. For example, economic approaches that enhance the subtle physicochemical differences between the individual CM elements provide an avenue toward enabling the market viability of production from lower-grade ore and unconventional resources. Understanding of the coupled reaction kinetics, thermodynamics, and mass transfer associated with multiphase fluid flow in environments with low Reynolds number will be particularly important in designing and optimizing efficient separation systems. Method development, including ligand design, flow configuration, and reactor conditions, will require screening techniques amenable to large sets of experimental conditions.

Megascale opportunities in microfluidics

An exciting set of opportunities exist for the LoC community to help in securing the supply of critical materials, from microfluidic flow devices that purify and separate CMs, to geochemical micromodels that give insights into extraction and reagent design. While polymer-based LoC technologies designed for biological compatibility are limited in applicability in the harsh temperature, pressures, and fluid compositions (pH, salinity) necessary for CM extraction and processing, advances in "hard" microfluidics (*e.g.*, glass, silicon, rock)[83–92] provide an avenue to leverage LoC techniques in meeting the critical materials supply gap. Below, we highlight a set of opportunities for microfluidics to this end along with recent LoC applications in securing critical materials.

Microfluidics

The compositional heterogeneity and complexity of solutions bearing critical materials (*e.g.*, brines produced from oil and gas or geothermal wells) require the design of customized reagents (ligands, solvents, *etc.*) and processing conditions (*e.g.*, pressure, temperature, pH, flow rates) to optimize their extraction and separation. Techniques amenable to rapid, inexpensive, and massively-parallelizable screening are needed.

Microfluidic approaches, well suited to the design, screening, and manipulation of microscale fluids and colloidal systems, are particularly amenable to the purification and separation of CMs owing to their small sample requirements, high throughput, rapid analyses, and multiplexing capabilities.[93] For example, dissolved species in homogeneous (*i.e.*, single-phase) solutions can be separated using field-flow fractionation methods that leverage cross fields (*e.g.*, electric or

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magnetic) to induce and/or enhance the spreading of solutes.[94] Charge- and size-based solute separation in single-phase fluids is likewise enabled *via* electro-osmotic flow (EOF), where bulk flow is induced in response to interactions between the charged species and the electric double layer at wall surfaces. Bottenus *et al.*[95] demonstrated rapid (<10 min) EOF-based separation of REEs (La through Pm), for example, by leveraging the increased ratio of surface area to volume of a fused-silica microchannel. Approaches that separate ionic species without the use of an external input (*e.g.*, heat, electric fields, and ligands) have also been sought. Recently, Wang *et al.* developed a laminar co-flow platform that separates Mg from Ca by maintaining a reactive interface with steep concentration gradients.[96] Research into the development and use of microfluidics for CM separation is in its early stages and is ripe with opportunities.

In two-phase fluid systems (*e.g.*, liquid–gas, liquid–liquid), interfacial hydrodynamics and thermodynamics can be leveraged to further improve the separation of dissolved species. Importantly, transport is enhanced in microfluidic platforms where capillarity enables passive flow. Recent advances include a thread-based device by Quero *et al.*[97] that leverages capillary electrophoresis to separate Li from K and Na, and a fiber-based microfluidic approach to crystallize lithium away from sodium by Chen *et al.*[98] Here, capillarity is leveraged to enhance the differential charges, solubilities, and diffusivities of the salts. Paper-based approaches used widely in biological sciences provide similar advantages in cost- and time-effective separation, yet their application in critical minerals is relatively unexplored.

In solvent extraction, the development of ligand species that facilitate the partitioning of CM species out of aqueous solutions will require rapid analyses and screening. Microfluidics is particularly amenable to this, given its short diffusion lengths, high ratio of surface area to volume, tight residence time distributions, and precise flow configurations. Microfluidic channel reactors, for example, enable rapid mass transfer across their narrow cross-sections, the parallelization of which allows for high-throughput (up to 1 L/h) solvent extraction.[99] Similarly, droplet microreactors generate colloids with precision, enabling the rapid screening of solvent compositions. Fernández-Maza *et al.* optimized the separation of Dy from La for a range of solvents, ligands, and aqueous phase pHs.[100] Microfluidics is primed to help understand and optimize CM separation, particularly aqueous species such as Li and Mg, and presents a set of exciting opportunities with which the LoC community can engage.

Geochemical microfluidics

The extraction of CMs, whether from conventional or secondary resources, will require understanding and optimization of the coupled reactive transport processes at fluid–solid interfaces. Here, many questions remain open, including the transport of multiphase fluids through porous or granular media, wetted reactive surfaces, coupling between transport and reactions, and the interplay between ionic species on extraction kinetics.

Microfluidic platforms that mimic the morphology of porous or granular media, so-called micromodels, enable the direct observation of wetting and multiphase flow phenomena through complex porous/granular geometries.[101–104] Flow configurations through resource materials, for example, determine the overall access and recovery rate of the embedded CMs. In porous/granular media, pore size heterogeneity leads to preferential flow paths where reagent delivery and residence times are nonuniform and the overall recovery rates are significantly reduced.[105,106] Further, heap and *in situ* leaching processes where aqueous reagents share pore space with air are dominated by multiphase flow characteristics.[106] Micromodels that replicate the pore geometry of CM-bearing resources provide insights into approaches that maximize the delivery of reagents throughout the pore space (*i.e.*, maximize the "sweep efficiency").

Extraction of critical minerals from their hosting matrices ultimately relies on the chemical interactions between fluids and mineral surfaces and requires probes that honor mineral chemistry. Geochemical microfluidics integrates the advantages of microfluidics with the mineral reactivity of geological and geologically derived material resources.[83–87,107] Notably, geochemical micromodels resolve the interplay between reactions and multiphase transport at fluid–mineral interfaces to understand the spatiotemporal associations of fluid phases, dissolved species, and interfacial reactions. For example, Gerardo *et al.* resolved the reactive transport mechanisms controlling REE leaching from coal ash to design low-reagent approaches for recovery from secondary wastes.[55,108] Interweaving the geochemistry of mineral-bearing resources with direct microscale visualization enables the cost- and time-effective screening of reagents as well as an understanding of fundamental reaction couplings at the pore/granular level.

Similarly, ore beneficiation often results in a distribution of grain sizes, including sub-micrometer particles (*i.e.*, "fines"). Fine particulates are prone to mobilization with changes to solution composition (*e.g.*, cation speciation, concentrations, pH, and temperature), the redeposition of which results in flow path obstruction (*i.e.*, formation damage) and the reduction of reagent access. Extractive processes that dissolve bulk minerals also contribute to dislodging fines, exacerbating their migration and impacting the accessibility of reagents to CM-bearing grains. Geochemically-functionalized micromodels, for example, provide a means of exploring these effects.[85,86]

Finally, elucidating fundamental reaction processes at mineral surfaces will require nanoscale resolution. Recent advances in nanofluidics enable the spatiotemporal resolution of dynamic fluid–solid interactions, including *operando* scanning electron microscopy devices,[88] to allow the study and design of fundamental coupled reactive transport processes underlying CM extraction at the interfacial- and molecular-levels. The ability to simultaneously capture the multiphase

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fluid dynamics and reactions at the porous/granular fluid–mineral interfaces in CM-bearing resources enables the determination, design, and optimization of their extraction viability, critical to the security of CM supply.

Overall, micro/nanofluidic resolution of coupled reactions and transport at fluid–mineral interfaces provides a fast and inexpensive approach to screen for reagent compositions, flow rates, and operational temperatures/pressures that optimize upscaled extraction operations such as those in heap leaching and hydrometallurgy. The mineralogical heterogeneities encountered in metal-bearing resources (*e.g.*, ore or industrial wastes, that hold REEs, Co/Ni, Cu, or PGEs) introduce a complex set of interfacial geochemical interactions that are not easily modeled. The spatial resolution of mineral phase distributions and their accessibility by reagents (*e.g.*, abutting pores or fractures) enabled by microfluidics, excitingly, allows for a fundamental understanding and modeling of the upscaled hydrometallurgical operation.

Conclusions

Ready availability of the elements critical to energy security, the so-called "critical minerals and materials", are of increasing importance and urgency. Challenges arise from the geographical concentration of the resources to their energy- and reagent-intensive processing. State-of-the-art approaches in the mining sector, particularly the REEs, rely on ecologically and economically costly hydrometallurgical approaches that render the domestic supply chain vulnerable to instability. Here, opportunities abound for the LoC community to assess unconventional resources and to develop new extraction approaches that are better aligned with the sustainability goals of low-carbon energy technologies. In particular, the small volumes, high throughput, and multiplexing capabilities of microfluidics are well suited to providing rapid characterization of material properties to aid with prospecting and to determine their physicochemical conduciveness to extraction. Likewise, characterization of the fundamental reactive transport processes that extract CMs from their granular host rock, including reagent screening to achieve extraction with low environmental impact, is well suited for geochemical micromodel studies. While the two communities have been isolated in the past, longstanding expertise in microfluidics to probe and control coupled flow and reaction through miniature, massively-parallelized systems is well suited to characterizing, screening, and optimizing the supply of critical materials. Likewise, the intersection of critical materials and minerals with micro/nanofluidics provides an exciting new frontier for the LoC community to tackle.

Conflicts of interest

There are no conflicts to declare.

Data availability

All data used in this article have been included in the cited works.

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