RARE EARTH ELEMENTS

V.G KUMAR DAS

RARE EARTH ELEMENTS

A Monograph by

V. G. Kumar Das

AKADEMI SAINS MALAYSIA

2026

RARE EARTH ELEMENTS

Academy of Sciences Malaysia
Level 20, West Wing, MATRADE Tower,
Jalan Sultan Haji Ahmad Shah,
off Jalan Tuanku Abdul Halim,
50480 Kuala Lumpur, Malaysia
Phone : +6 (03) 6203 0633
Fax : +6 (03) 6203 0634
www.akademisains.gov.my

Preamble

This monograph responds to a request from ChM Dr Yang Farina Abdul Aziz FASc, Head of the Chemical Sciences Division at the Academy of Sciences Malaysia (ASM), to disseminate key information on rare earth elements (REE) to Fellows within and across various disciplinary divisions. It also aims to explain why these elements have become a focal point of global attention. This request arose from our presentation of observations to the Academy following our site visit in August 2024, conducted alongside Professor Abu Bakar Sulong, to the pilot-plant facility of a local company in Bukit Beruntung engaged in processing rare-earth elements. I will also elaborate on these points in this article.

A. Introduction

With that preamble, let me start by recalling your school-day memory of these elements, which you might remember are located at the bottom of the Periodic Table. It is understandable if you once thought they were unimportant. However, their significance has increased sharply in recent years. In truth, these elements are vital to the operation of our modern technology. If they were to become unavailable or truly scarce, many of the devices and systems we rely on daily would stop working immediately. In fact, they are not particularly rare. They are widely spread in the Earth's crust; many of them (La, Ce) are as common as copper. Their name – "rare earths" - is a leftover from the first discovery of Yb found in small amounts near Ytterby, Sweden, in the 18th century, while "earth" was an old term for acid-soluble oxides. They appear as oxides or phosphates alongside other minerals, such as monazite, bastnäsite, and ion-adsorption clay deposits, rather than as isolated rare-earth minerals, which could otherwise be mined more cheaply. Their "rare" moniker persists because they do not often occur at easily mined concentrations. Their very similar properties also make individual separation more challenging. These similar properties stem from their electronic structures, which include 4f orbitals.

RE metals are in Period 6 of the Periodic Table. There are 14 of them (elements 57-70 from Lanthanum to Ytterbium), characterised by the gradual filling of their 4f orbitals. The unpaired electrons in these orbitals give them paramagnetic properties. These metals include the transition metals Scandium (Sc), Yttrium (Y), and Lutetium (Lu), which are often found with them in mineral deposits and share similar chemical properties.

Rare Earth Elements

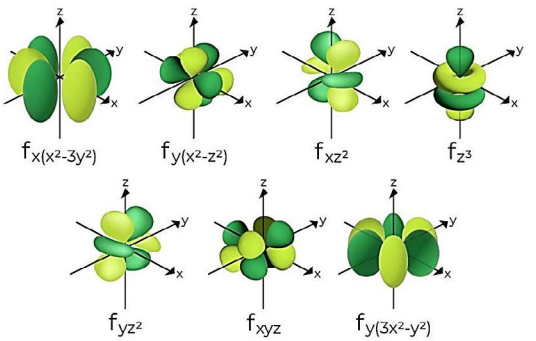
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La-La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt									

Lanthanides

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

Actinides

Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



Shape of f-orbital

The dark green zones indicate regions where the wave functions have positive values, and the light green zones indicate regions where the wave functions have negative values.

These relatively diffuse 4f orbitals (with seven possible M_l values: -3, -2, -1, 0, 1, 2, 3) poorly shield the 5d and 6s orbitals from the nuclear charge, making them more strongly attracted to the nucleus. Additionally, in heavy elements, relativistic effects shrink the inner s and p orbitals, which increases the effective nuclear charge felt by the outer electrons.

This contraction reduces the shielding provided by these inner electrons somewhat, thereby strengthening the pull of the nucleus on the valence electrons. Across the lanthanide series (La to Lu), the result is a gradual decrease in atomic and ionic radii—a phenomenon known as the lanthanide contraction.

Symbol	At. No	Oxidation state			Outer electronic configuration			
					Atom	M^{2+}	M^{3+}	M^{4+}
La	57	-	+3	-	$4f^0\ 5d^1\ 6s^2$	-	$4f^0$	-
Ce	58	-	+3	+4	$4f^2\ 5d^0\ 6s^2$	-	$4f^1$	$4f^0$
Pr	59	-	+3	+4	$4f^3\ 5d^0\ 6s^2$	-	$4f^2$	$4f^1$
Nd	60	+2	+3	+4	$4f^4\ 5d^0\ 6s^2$	$4f^4$	$4f^3$	$4f^2$
Pm	61	-	+3	-	$4f^5\ 5d^0\ 6s^2$	-	$4f^4$	-
Sm	62	+2	+3	-	$4f^6\ 5d^0\ 6s^2$	$4f^6$	$4f^5$	-
Eu	63	+2	+3	-	$4f^7\ 5d^0\ 6s^2$	$4f^7$	$4f^6$	-
Gd	64	-	+3	-	$4f^7\ 5d^1\ 6s^2$	-	$4f^7$	-
Tb	65	-	+3	+4	$4f^9\ 5d^0\ 6s^2$	-	$4f^8$	$4f^7$
Dy	66	-	+3	+4	$4f^{10}\ 5d^0\ 6s^2$	-	$4f^9$	$4f^8$
Ho	67	-	+3	-	$4f^{11}\ 5d^0\ 6s^2$	-	$4f^{10}$	-
Er	68	-	+3	-	$4f^{12}\ 5d^0\ 6s^2$	-	$4f^{11}$	-
Tm	69	+2	+3	-	$4f^{13}\ 5d^0\ 6s^2$	$4f^{13}$	$4f^{12}$	-
Yb	70	+2	+3	-	$4f^{14}\ 5d^0\ 6s^2$	$4f^{14}$	$4f^{13}$	-
Lu	71	-	+3	-	$4f^{14}\ 5d^1\ 6s^2$	-	$4f^{14}$	-

Lanthanides primarily show a stable +3 oxidation state, but some elements like Eu, Sm, Yb also readily form stable +2 ions, while Ce, Pr, and Tb can achieve +4 states, making them good oxidisers.

$$2Ce^{4+}(aq) + H_2O_2(aq) \rightarrow 2Ce^{3+}(aq) + O_2(g) + 2H+(aq)$$

The stability of the +2 oxidation state in Eu, Sm, and Yb ions arises from their half-filled ($4f^7$) or filled ($4f^{14}$) subshells.

Nowadays, this oxidation state has been extended to nearly all other lanthanides except radioactive promethium, by employing bulky, sterically hindered ligands (for example, substituted cyclopentadienyls) that encase the metal and shield it from oxidation (see Figures 1–2; Reference 1).

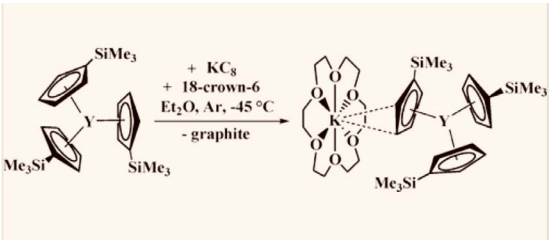


Figure 1

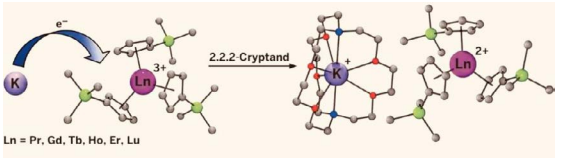


Figure 2

B. Classification

Light REEs – Lanthanum (La) through Gadolinium (Gd); found in bastnasite and monazite; uses: polishing powders, catalysts, magnets, digital camera lenses, hybrid car batteries (anodes in the form of mischmetal Ni hydride alloys).

Heavy REEs – Terbium (Tb) through Lutetium (Lu) (plus Yttrium); found in xenotime and ion-adsorption clays; uses: high-performance magnets (wind turbines, EVs), medical tech, smartphone screens, phosphors for LED lighting, lasers.

C. REE Reserves, Production Statistics & Market Demands

Top 6 countries by REE Reserves (million metric tons):

China (44), Brazil (21), India (6.9), Australia (5.7), Russia (3.8), Vietnam (3.5)

Top 6 countries REE production (kilometric tons):

China (270)*, USA (45), Myanmar (31), Australia (13), Thailand (13), India (2.9)

(*One tenth of this consists of heavy rare earth elements (HREE), with China dominating their production, as the rest of the world lacks the operational commercial capacity to efficiently separate the HREEs needed to produce high-coercivity RE permanent magnets.)

Peninsular Malaysia's RE ore deposits are found not only in monazite minerals, where they coexist with radioactive thorium, but also more abundantly in non-radioactive lateritic ion adsorption clays (IAC), where they largely exist as REE ions adsorbed on clay minerals through ion exchange

and surface complexation. Malaysia has an estimated 18.2 million tonnes of REE reserves, valued at over RM900 billion (Figure 3). The New Industrial Master Plan 2030 identifies REEs as a strategic driver. While the plan prohibits the export of unprocessed or raw REEs, it encourages foreign investors to participate in both upstream (refining) and downstream (magnet manufacturing) ventures in the country. The Ion Adsorption Clays (IACs) are found in weathered granitic profiles across Peninsular Malaysia, as shown in the geological chart below. Economic and technical factors would determine how much of these could be mined.

Thus, the raffinate (aqueous phase) becomes progressively depleted of the target solute through a series of repeated mixing and settling stages, during which it continuously encounters a fresher organic solvent.

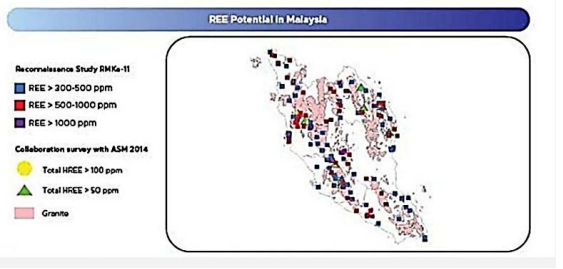


Figure 3. Distribution of IAC rare earth resources in Peninsular Malaysia Source: Malaysian Department of Minerals and Geoscience

The IAC REE deposits typically contain 33.89% PrNd, 0.71% Tb, and 3.22% Dy, in contrast to monazite-based ores, which have values of 22.5, 0.27, and 1.26%, respectively. [Pr = praseodymium, Nd = neodymium, Tb = terbium. Dy = dysprosium]

(All percentages are typically reported as per industrial practice in fractional percentages, i.e. ratio of target REE oxide/total REE oxides).

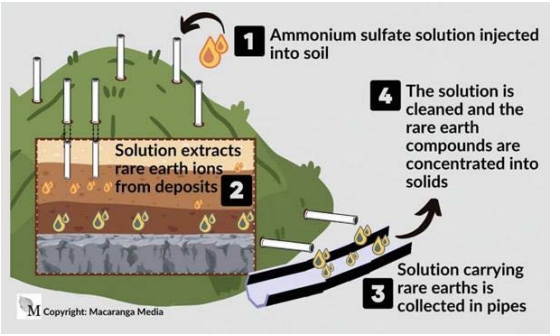
Rare Earth Metal Market

The Rare Earth Metal Market is characterised by a complex competitive landscape, driven by increasing demand across sectors such as electronics, renewable energy, and defence. Key players such as China Northern Rare Earth Group (CN), Lynas Corporation (AU), and MP Materials (US) are strategically positioned to leverage their operational strengths. According to Market Research Future analysis, the rare earth metal industry is projected to grow from 6.75 billion USD in 2025 to 12.2 million USD by 2035, exhibiting a compound annual growth rate (CAGR) of 6.08%. Geopolitical tensions are likely to affect the rare earth metal market, as countries seek to secure their supply chains.

D. Extraction of REEs from mineral sources

REEs are extracted from IAC resources using the hydrometallurgical method. A suitable lixiviant, such as Ammonium Sulphate or Magnesium Sulphate, is employed to leach the REE values from the deposits. Leaching can be carried out using heap leaching, tank leaching, or in-situ leaching (ISL). Due to the low REE concentration in IAC deposits (generally around 500 ppm), in-situ leaching (graphically shown below) is preferred to avoid the costly double handling of the excavated ore and the subsequent disposal of the tailings. ISL also offers the additional benefit

of preserving the original vegetation of the mining site.



Source: Macaranga Media

Rich liquor from the leaching operation is called pregnant leach solution (PLS). PLS from the leaching operation will first be purified by removing aluminium, iron, and other heavy metals via carbonate/sulphide precipitation at a controlled pH (to prevent loss of REE values). The REE in the purified PLS is conventionally precipitated as a mixed rare-earth carbonate (MREC) and then converted to an aqueous chloride feed for subsequent solvent extraction using an organic solvent with an acidic extractant.

Due to the low concentration of REE in the PLS (usually 1 kg REE per m^3 PLS), the mining operation must process large volumes of PLS to obtain economically viable quantities of MREC. Conventional operations require multiple large-volume precipitation and settlement ponds. These ponds, covering over 10 acres, pose an environmental hazard, as unscrupulous miners may abandon them after mining, leading to environmental damage as seen in the IAC operations in Northeast Myanmar (Saulang).

A Malaysian company, Malaco Mining Sdn Bhd (MALACO), has invented a green mining method for IAC deposits called GNano Process (patent pending), which uses an innovative approach to hasten the precipitation and settling.

The solvent extraction (SX) technique (also known as liquid-liquid extraction) is widely used in the rare earth industry for the most cost-effective separation of REEs compared to other techniques based on ion exchange or membrane separation.

As the two phases mix, the desired solute is selectively transferred from the aqueous to the organic phase, which is composed of an extractant and a diluent. The two immiscible phases are then separated by differences in density, and the desired component may be recovered by further processing.

This liquid-liquid extraction technique is best performed industrially using a mixer-settler cascade to efficiently separate components between the aqueous feed solution and the organic solvent.

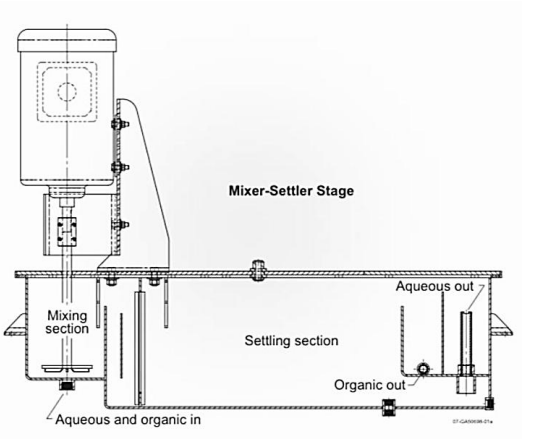


Figure 4. Diagram of a mixer-settler unit (Reference 2)

Each mixer-settler provides a single stage of extraction (Figure 4). The two phases enter the mixing section, where they are mixed by an impeller. The two-phase solution flows into the settling section, where it separates by gravity due to the density differences of the phases. Typical mixing and settling times are on the order of a few minutes. The separate phases exit the settling section by flowing over a weir (organic solution) or through an underflow, then over a weir (aqueous phase). The separation interphase is controlled by the height of the weir on the outlets of the settler section

Multiple mixer-settler units are connected in a counter-current arrangement. In this setup, the feed, or PLS, enters stage N, while the fresh organic solvent enters stage 1 (Figure 5). This maintains a high concentration gradient, or 'driving force,' for efficient mass transfer throughout the process. Several solvent extraction cascades are employed in an overall flowsheet that extracts, purifies, and recovers the target REEs..

A typical flowsheet is shown in Figure 6. This consists of a saponification section for pH control (this is required before each extraction sequence as the pH of the aqueous phase decreases during the sequence), an extraction section, a scrub section (achieved with an aqueous solution that alters the acid or REE equilibrium conditions), and a strip section (where the REE is recovered from the organic phase as a rich liquor (RL) product). The organic phase, now stripped of any solutes, is recycled for reuse.

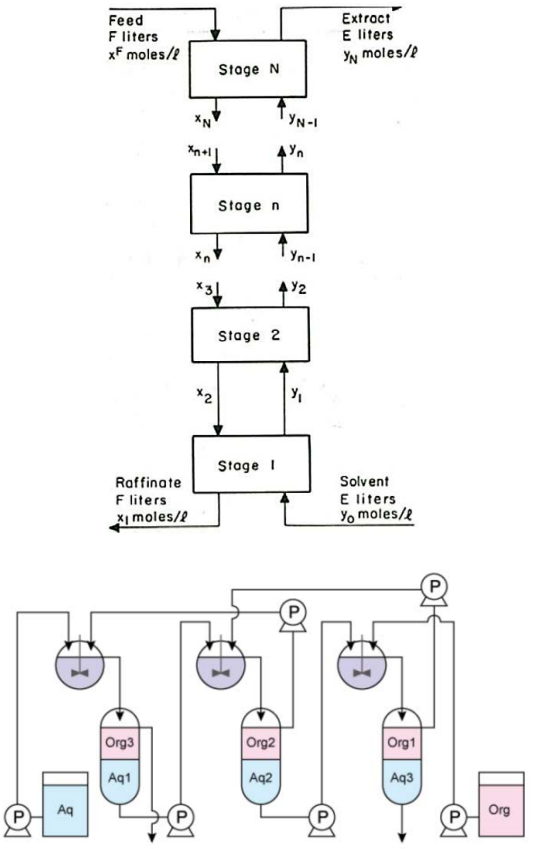


Figure 5. Countercurrent-multistage extraction process flow diagram

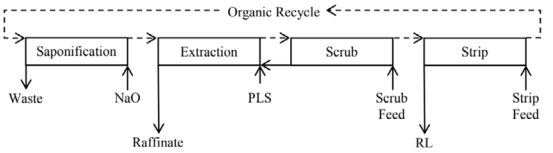
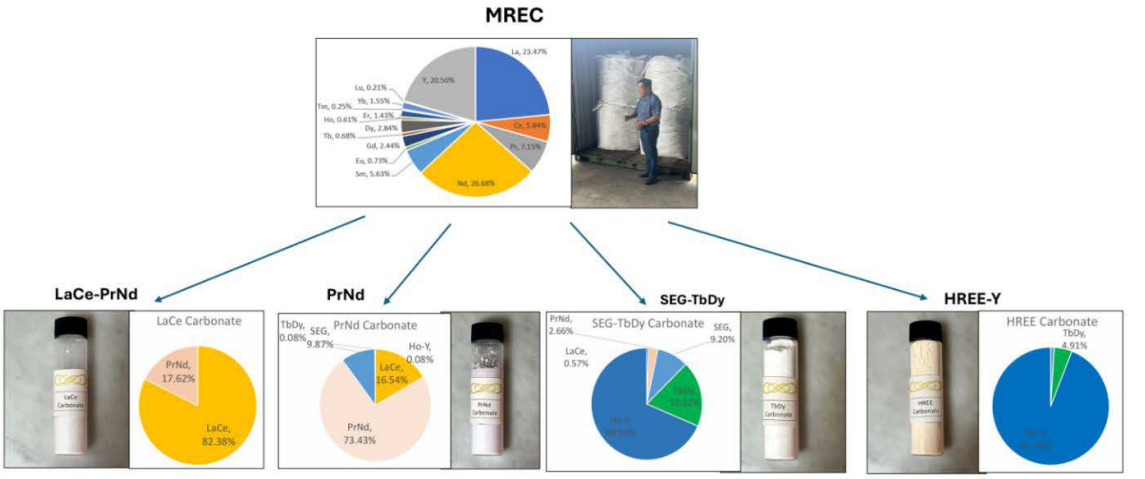


Figure 6. Simplified design of a single REE solvent extraction circuit (Reference 3)

Pilot-scale multistage mixer-settler cascade

E. Indigenous production of Rare Earth products by Malaco Mining Sdn. Bhd. at its proof-of-concept (POC) semi-commercial total REO separation plant in Simpang Pulai, Ipoh.

The company, led by geologist Dato' Sia Hok Kiang, FASc, has successfully separated four groups of REEs that are vital components of the industry chain: LaCe (Lanthanum Cerium), PrNd (Praseodymium Neodymium), SEG (Samarium Europium Gadolinium), and HREE in December 2024.



Products from the Malaco POC Plant

Upon receipt at the POC plant, the MRECs were dissolved in HCl to form a RE chloride solution, which was used as feed to Malaco's SX process (100 g/L at pH 4.5). This constituted the aqueous phase. The organic phase consisted of a selected, highly surface-active, acidic extractant, such as Di(2-ethylhexyl) phosphoric acid [which exists as the dimer $(HDEHP)_2$], dissolved in an organic diluent. HDEHP interacts with rare earth metals at the aqueous-organic interphase to form stable, extractable complexes. The rare earth metal ions, typically in their trivalent oxidation state (RE^{3+}), exchange with the acidic protons of the HDEHP dimer to form $RE(DEHP)_3$ or, more often, $RECl(DEHP)_2$, which is soluble in the organic phase.

Beyond the established HDEHP/SX flow at Malaco, metal-organic framework (MOF) based solid-phase extraction is being explored as a targeted, non-commercial pathway for REE enrichment from acidic feeds. Water-stable MOFs with suitable functional groups or open metal sites could enable selective uptake of REEs from acidic feeds, enabling pre-concentration or polishing ahead of, or in parallel with, the SX step. While not yet commercialised, this approach is being evaluated for its potential to reduce solvent load, enhance separation of closely related REEs, and permit regeneration over multiple cycles (Reference 4).

The diluent used by Malaco was a proprietary formulation called G-solvent, which has a high flash point to reduce risk of fire at the separation plant. The extractant concentration was approximately 0.5 molarity, and the organic/aqueous ratio was adjusted to optimise REE separation. The organics, i.e., the extractant plus diluent, were saponified before each extraction sequence involving multiple stages, as the pH of the aqueous phase decreased during the sequence.

Back extraction (stripping) of the REE-loaded organic phase (hereinafter referred to as oil) is carried out in stages of increasing HCl concentration to remove different groups of REE from the loaded oil. The final spent oil (extractant + diluent) is stripped with a strong acid, washed, saponified, and then reused. The aqueous HCl phase, after several rounds of SX, is treated with ammonium bicarbonate to precipitate the residual RE carbonate, and the decanted ammonium chloride is sold as fertiliser. Therefore, in a sense, there is no effluent problem in the SX process. RE carbonates readily convert to oxides upon calcination, which are widely utilised across various industries, especially in the electronic and automotive sectors.

Malaco has obtained full REE separation technology through a technical collaboration agreement with Carester, a French REE company whose REE separation experts were key technologists of Rodia La Rochelle, the first commercial REE separation company in the world in the 1960s. Malaco is now building a POC plant for complete TREO separation with a capacity of 3,000 tonnes per year, aiming for commissioning in April 2026. They plan to expand this capacity to 10,000 tonnes per year using adjacent industrial land. Malaco has dedicated

much of the past year to identifying the best method for producing REE products free of radioactive contamination. **All IAC deposits naturally contain uranium and thorium. During rare earth leaching with ammonium sulphate, uranium and thorium can be retained in the deposit by carefully controlling the pH, resulting in a leachate free of uranium and thorium (U-238 and Th-232 < 1 Bq/g)**. However, some producers intentionally use lower pH levels to extract higher REE quantities, which also pulls out more radioactive material. An often-overlooked risk is that a particularly concerning decay product of Uranium-235 is Actinium-227, a long-lived ($t_{1/2}$ = 21.8 years) highly radioactive alpha-emitter, always present in trace amounts and difficult to detect.

Malaco Mining has now developed a proprietary process to produce radionuclide-free solutions at the mine site (Ref. HK Sia: private communication). It bypasses the need for RE carbonate generation: the prepared REE-rich aqueous solution, freed from common metal impurities through pH adjustments and precipitating additives, is delivered directly into their mixer-settler cascade, where pH adjustments are made as appropriate.

F. REE Applications

<u>Use of RE metals in modern high-strength permanent magnets</u>

NdPr oxide is used in the production of permanent $Nd_2Fe_{14}B$ magnets, which have found critical applications in electric vehicles, power-generating wind turbines, and industrial electric motors. **These magnets constitute 92% of the REE value chain.**

A point to note about DyTb is its role in enhancing the coercivity (resistance to demagnetisation) of neodymium rare earth permanent magnets. Each tonne of Nd-Fe-B rare earth magnets requires the addition of 12-24 kg of DyTb for this purpose. This accounts for 5% of REEs, with PrNd comprising 30%. This ensures that the magnets remain within their specified use parameters when subjected to repeated cycles of heating and cooling and retain their magnetic strength even when heated to 200 °C, as in the applications mentioned above.

Iron is the primary source of the high saturation magnetisation in NdFeB magnets, with Boron being a vital component in forming the precise tetragonal crystal structure that endows the magnet with exceptional magnetic properties, while Nd provides the magnetocrystalline anisotropy to align the magnetic moments, thereby reducing their susceptibility to demagnetisation (coercivity enhancement). Due to their high iron content, NdFeB magnets are highly vulnerable to corrosion and often feature a three-layer Ni-Cu–Ni coating.

SmCo

NdFeB

Samarium-cobalt (Sm_3Co_7) magnets are less strong than NdFeB magnets but offer superior high-temperature performance (up to 300°C), reliable coercivity, and inherent corrosion resistance, requiring no coating.

Powerful permanent magnets made from these rare earths are used in modern wind turbines, in drive motors of many **EVs**, and in electronics and landing gear motors in **civil and military aircraft.**

Use of REs in superconducting systems

Rare earth elements (RE) are commonly used in superconducting systems to tune the structure and electronic environment rather than to form the superconducting pairs themselves. In **cuprate (e.g., $REBa_2Cu_3O_{7-\delta}$) and iron-based superconductors**, RE ions occupy lattice sites that influence crystal structure, lattice parameters, oxygen ordering, and carrier concentration in the active superconducting layers. The superconducting condensate mainly resides in the conducting planes (e.g., the CuO_2 planes in cuprates), while the RE sublattice carries local magnetic moments that can be accommodated or adjusted to avoid disrupting superconductivity. Magnetic moments from REs can be present without destroying superconductivity, though very large moments can compete with or suppress certain pairing states. The effect of RE substitution is material-specific but often beneficial for Tc and current-carrying capacity. The ionic radius of the RE ion can exert chemical pressure, subtly altering bond angles and lattice constants and influencing Tc in some families. RE-related defects and secondary phases can also serve as flux-pinning centres, thereby improving the critical current density in magnetic fields. Tc values depend on the exact composition, oxygen content, and processing conditions. For optimally oxygenated $YBa_2Cu_3O_{7,}$ Tc is on the order of 92-93 K, allowing cooling via inexpensive liquid nitrogen, rather than liquid helium.

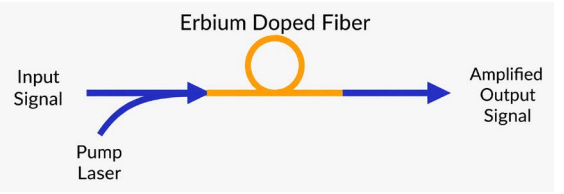
Emerging low-helium MRI systems employ closed-loop high-temperature superconducting coils, like YBCO. Once energised, the resistance-free current continues to circulate in the closed loop indefinitely without needing a power supply, maintaining the magnetic flux as long as temperature and operational limits are observed.

Separately, **rare-earth hydrides** at megabar pressures form a unique class of superconductors in which dense hydrogen networks and electron–phonon coupling induce superconductivity with relatively high Tc; in these systems, the chemistry is more intricate than simple electron donation or cage formation.

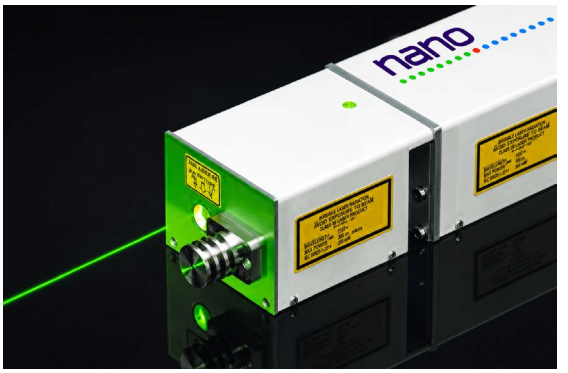
Other application areas of rare earths

Four other areas that may interest our readers are **lasers, medical applications, glass, and catalysis**

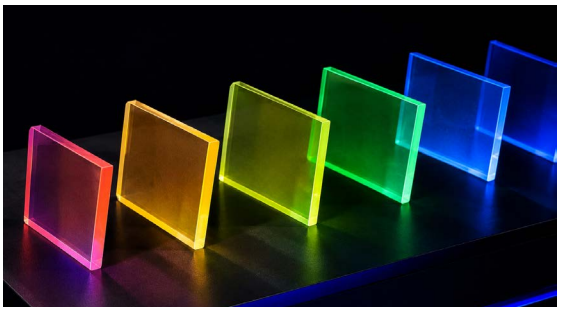
An **erbium-doped fibre laser (EDFL)** is a type of laser that uses an optical fibre doped with erbium ions (Er^{3+}) as the gain medium for long-distance fibre optic communication.



Yttrium-aluminium-garnet (YAG) is a common medium for solid-state lasers. When doped with erbium, YAG lasers produce wavelengths of focused light useful for oral surgery and dentistry. Nd: YAG lasers are widely used to remove hair follicles.



Many REs find medical applications based on their magnetic and optical properties, including as contrast agents (e.g., Gd in MRI), phosphors and scintillators (e.g., Tb, Gd) in medical imaging, and as lasers for surgery (e.g., Er, Ho, Tm).



REs (e.g. Ce, Nd, Pr, Ho) colour and decolourise glass, absorb UV light, provide a high gloss in polishes, and protect glasses and mirrors from dulling

Because of their unique 4f electron structures, which confer excellent redox properties and oxygen storage/ release, REEs are widely used as catalysts. Primary examples include:

- **Automotive Catalytic Converters:** Ce and La are crucial components in three-way catalysts (TWCs) for gasoline engines. Cerium readily switches between its Ce^{3+} and Ce^{4+} oxidation states, allowing it to store and release oxygen as needed to convert poisonous carbon monoxide (CO) into non-toxic carbon dioxide (CO_2) and reduce nitrogen oxides (NO_x).

$$2NO_x \rightarrow xO_2 + N_2$$
$$2CO + O_2 \rightarrow 2CO_2$$
$$C_xH_{2x+2} + \left[\frac{3x+1}{2}\right] O_2 \rightarrow xCO_2 + (x+1)H_2O$$

- **Petroleum Refining**: Rare earths, particularly Ce and La, are fundamental ingredients in **fluid catalytic cracking (FCC) catalysts**. They are typically incorporated into zeolite catalysts to mitigate the effects of metal contaminants, prevent the loss of acid sites during FCC unit operation, improve thermal stability, and enhance the yield and purity of products such as gasoline from crude oil.

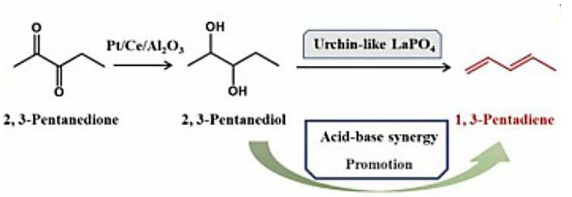
- **Industrial Air Purification**: Rare earth catalytic materials (e.g. CeO_2, La_2O_3, Pr_6O_{11}, Tb_4O_7) are used for the catalytic combustion of methane and volatile organic compounds (VOCs), helping to purify industrial waste air.
- **Specialised Reactions**: Neodymium and europium oxides have been investigated as catalysts for various organic reactions and for the degradation of pharmaceutical pollutants in water through photocatalysis. Praseodymium-based catalysts have also shown promise in electrochemical CO_2 reduction reactions.

  Rare earth elements (REEs) are increasingly vital catalysts in **organic synthesis**, offering unique Lewis acidity, variable oxidation states (like Ce[III]/Ce[IV]), and high coordination ability to activate organic molecules, promoting reactions like C-C coupling, hydrogenation, and cycloadditions, often with enhanced selectivity and stability, acting as supports, promoters, or active sites in new systems like MOFs (Ce-doped MOFs show promise in electrocatalysis) or doped materials.

- They offer advantages over traditional catalysts, enabling more efficient, milder conditions and greener synthesis routes, including recycling from e-waste for Michael additions and Diels-Alder reactions.

Applications in Organic Synthesis

- **C-C Bond Formation**: Catalyse Michael additions, Diels-Alder reactions, and Friedel-Crafts, mainly due to their efficacy as Lewis acids. E.g. $RE(OTf)_3$ (RE = Sc, La; $OTf^- = CF_3SO_3^-$)
- **Hydrogenation & Dehydrogenation:** Efficiently catalyse hydrogenation of phenols to benzene and other reductions. E.g. Tb and Ho are used in mixtures with alumina and cerium.
- **Dehydration of alcohols:** $LaPO_4$ has proven to be an excellent green catalyst for dehydrating light alcohols and diols such as 2,3-pentanediol derived from bio-based 2,3-pentadione. In the latter case, the precise regulation of the catalyst's acid-base sites (acid/base ratio of 2.63) yields high amounts of 1,3-pentadiene with minimal formation of the isomeric 1,4-pentadiene and also suppresses pinacol rearrangement (Reference 5). 1,3-pentadiene has wide applications in the production of adhesives, curing agents, and paints.



- **Olefin Polymerisation:** Efficiently catalyse dienes (like isoprene) and cyclic esters, due to their large ionic radii, high Lewis acidity, and oxophilicity, enabling precise control over polymer structure (stereoselectivity) and molecular

weight, often outperforming traditional catalysts. E.g. Trivalent lanthanum metallocenes.

- **Green Chemistry:** Recycled REEs from e-waste (like Yttrium oxide) are used, improving sustainability. $RE(OTf)_3$ are stable in water and recoverable for use as 'green' catalysts

References

1. MacDonald, M.R., Ziller, J.W. and Evans, W.J. (2011), *Journal of the American Chemical Society*, 133(40), pp. 15914–15917; MacDonald, M.R., Bates, J.E., Ziller, J.W., Furche, F. and Evans, W.J. (2013), *Journal of the American Chemical Society*, 135(26), pp. 9857–9868.

2. Law, J.D. and Todd, T.A. (n.d.) *Liquid–Liquid Extraction Equipment.* Idaho National Laboratory. Available at: https://www.academia.edu/figures/14236535/figure-4-pulse-column-with-perforated-plates

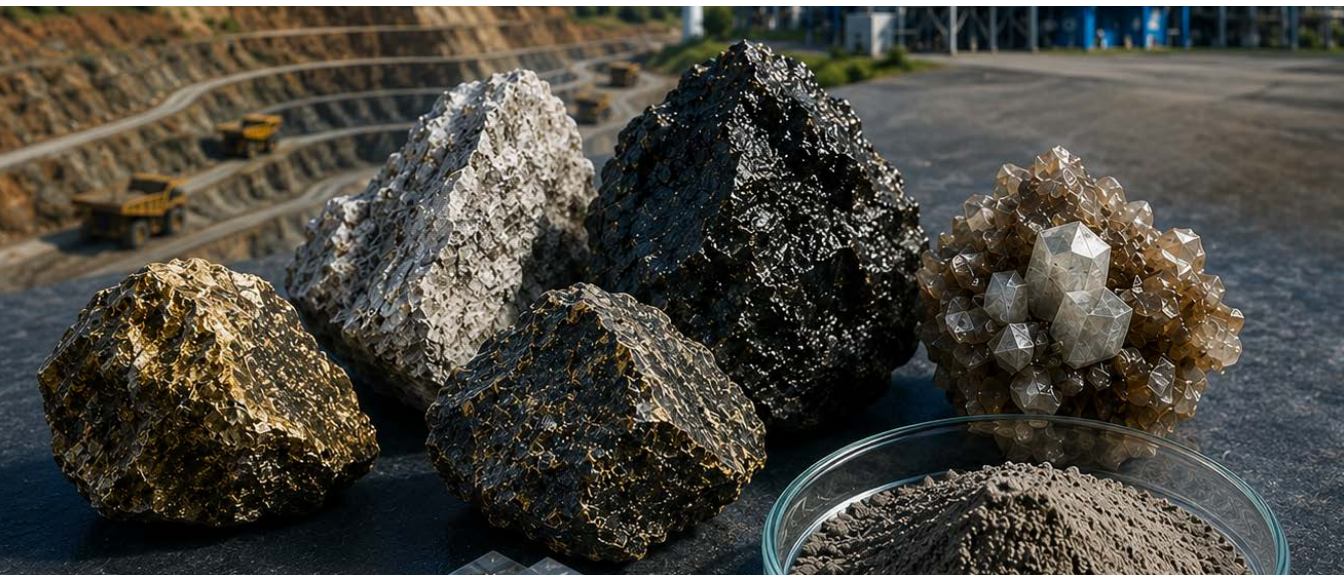
3. Lyon, K., Greenhalgh, M., Herbst, R.S., Garn, T., Welty, A., Soderstrom, M.D. and Jakovljevic, B. (2016) *Enhanced Separation of Rare Earth Elements*. 2016 International Mineral Processing Congress. Idaho National Laboratory, INL/CON-15-37552

4. Sutherland, C., 2025. *Rare earth recovery using metal–organic frameworks: advances, challenges, and future directions. Academia Environmental Sciences and Sustainability*, 2(2).

5. Feng, R., Qi, Y., Liu, S., Cui, L., Dai, Q. and Bai, C. (2022), *Applied Catalysis A: General,* 633, 118514

Acknowledgements

The author wishes to thank Dato' Sia Hok Kiang FASc, of Malaco Mining Sdn. Bhd., for permission to reproduce the graphics in Section E of this monograph.



Rare Earth Elements (REEs) shape the modern world in ways few substances do. This lucid monograph unpacks what REEs are, provides a clear overview of their chemistry and abundance, dispels common misconceptions, explains how they are mined, and describes the sophisticated pathways that recover them—whether as pure elements or as complex mixtures critical to advanced technologies. It highlights their key applications—from electronics and renewable energy to defence, medical imaging, catalysts, and emerging quantum technologies—and surveys the geopolitical landscape surrounding supply, demand, and strategic dependencies.

V.G. Kumar Das is an Emeritus Professor and a senior fellow (Academician) of the Malaysian Academy of Sciences; also, a fellow of The World Academy of Sciences. A Colombo Plan scholar and graduate of the University of Queensland (Australia), he has won national and international laurels for his work on tin-based chemicals at the University of Malaya (UM), where he had a distinguished academic career as the first holder of the Chair of Inorganic Chemistry and served several terms as Dean of the Faculty of Science.

Following retirement from UM, he rose to become the Founding Vice-Chancellor and Chief Executive of two private universities- AIMST University in Kedah, and Quest International University in Perak.

He has authored numerous journal publications and four scientific books relating to his interdisciplinary research encompassing chemistry, biology, and materials science. He has recently authored three biographies, including an institutional biography, and three works of fiction, earning him recognition as a novelist. This book adds to his collection of technical writings.

Academy of Sciences Malaysia
Level 20, West Wing, MATRADE Tower,
Jalan Sultan Ismail Haji Ahmad Shah,
off Jalan Tuanku Abdul Halim,
50480 Kuala Lumpur, Malaysia

Phone : +6 (03) 6203 0633
Fax : +6 (03) 6203 0634