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Sustainable **Critical Mineral Resource** Development
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Technology for rare earth ore beneficiation in Vietnam

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ABSTRACT

This report presents an assessment of the current state of research on rare earth ore beneficiation technology in Vietnam. Accordingly, beneficiation technologies are a combination of methods (depending on the characteristics of the main mineral and associated minerals): (1) gravity separation – magnetic separation – flotation; (2) gravity separation; (3) magnetic separation – gravity separation; (4) flotation; (5) gravity separation – flotation. The research primarily focuses on the ore deposits of North Nam Xe, South Nam Xe, Dong Pao, and Yen Phu, as well as some marine placer deposits. The technologies are presented as an overview of the characteristics of the head ore, the results achieved, and the proposed technology scheme. Most research reports have REO content of 30%–35% with a maximum recovery of 67.1%. The report also presents the challenges and opportunities in the current context for developing rare-earth mining, processing, and utilization technologies.

Keywords: *rare earth, mineral processing, gravity separation, flotation, magnetic separation*

1. Introduction

Rare earth elements (REE) comprise fifteen metallic elements of the lanthanide series, along with structurally similar yttrium and scandium (Gupta, 2005). This group of elements is divided into two subgroups. The "light" rare earth elements (LREE) group includes La-Eu, and the "heavy" rare earth elements (HREE) group includes the remaining lanthanide elements, Gd-Lu, and yttrium (Gupta, 2005; Trifonov, 1963). Scandium is generally not included in either the LREE or HREE classifications (Gupta, 2005).

Rare earth applications are widely used in high-tech industries such as (1) Electronics: television screens, computers, mobile phones, silicon chips, computer monitors, long-life rechargeable batteries, camera lenses, light-emitting diodes (LEDs), compact fluorescent lamps (CFLs), baggage scanners, marine propulsion systems; (2) Industrial manufacturing: high-strength magnets, metal alloys, stress gauges, ceramic pigments, colorants in glass, chemical oxidizers, polishing powders, plastic manufacturing, additives to enhance the strength of other metals, automotive catalytic converters; (3) Medical science: portable X-ray machines, X-ray tubes, magnetic resonance imaging (MRI) contrast agents, nuclear medicine imaging, cancer treatment applications and gene screening tests, medical and dental lasers; (4) Technology: lasers, optical glass, optical fibers, masers, radar detectors, nuclear fuel rods, mercury vapor lamps, high-reflectivity glass, computer memory, nuclear batteries, high-temperature superconductors; (5) Renewable energy: hybrid cars, wind turbines, next-generation rechargeable batteries, biofuel catalysts; and (6) several other applications: Eu is used as a way to identify valid banknotes for the Euro money supply and to prevent counterfeiting. It is estimated that 1 kg of this rare-earth element is present in a typical hybrid car. Ho is the element with the highest magnetic strength of all elements and is used to create extremely strong magnets. This application can reduce the weight of many motors (Balaram, 2019).

To effectively recover and utilize rare earth minerals, as with other strategic minerals, it is necessary to overcome limitations in raw material supply and to achieve full participation in the production and supply chains of materials serving high technology, clean energy, and digital transformation. The rare earth industry, therefore, needs to comprise three components (Tran Thanh Hai, 2025; Heydari, 2025).

- Upstream: including research on potential, assessment of reserves, mining conditions, mining techniques, mine development, and environmental issues related to mining (Tran Thanh Hai, 2025; Heydari, 2025).

- Midstream: including techniques and technologies for recovery, processing, and refining to recover metals/metal groups and related environmental treatment (Tran Thanh Hai, 2025; Heydari, 2025).

- Downstream: including technologies for manufacturing alloys, permanent magnets, energy batteries, materials, and other applications of rare earths as proposed above, and other end products from various scientific and technological fields (Tran Thanh Hai, 2025; Heydari, 2025).

In the midstream, rare-earth beneficiation technology has already been extensively researched and has achieved positive results. However, all rare-earth ore beneficiation technologies in Vietnam have remained mainly at the laboratory and pilot scales, with few significant industrial applications. Based on pilot-scale tests, several studies on the ore-processing technology for the Nam Xe, Dong Pao, and Yen Phu mines, several marine placer deposits, and several processing flowsheets have been proposed. The research results can be applied to production. Until now, some research results on monazite recovery from marine placers have already been applied (Nhu, 2021). This article presents case studies of rare-earth ore beneficiation technologies to date, focusing on primary ore deposits, highlighting opportunities and challenges for the near term, and outlining prospects for industrial applications.

2. Rare earth minerals in Vietnam

In nature, rare-earth elements occur in minerals. Rare earth minerals can be classified into several groups based on their rare earth element content. These minerals can be identified as cerium- or yttrium-type minerals based on the distribution of lanthanides within the mineral, which belong to the "light" or "heavy" rare earth groups described above (Cesbron, 1986). Alternatively, they can be complex minerals with a rare-earth element distribution encompassing all lanthanides, or selective minerals with a distribution encompassing only some lanthanides (Ferron, 1991).

Generally, rare earth minerals exist in the groups of carbonates, silicates, halides, oxides, and phosphates. Some common rare earth-containing carbonate minerals include Ancylyte(Ce) $Sr(Ce,La)(CO_3)_2OH.H_2O$, Ancylyte(La) $Sr(La,Ce)(CO_3)_2OH.H_2O$, Bastnaesite(Ce) $(Ce,La)(CO_3)F$, Bastnaesite(La) $(La,Ce)(CO_3)F$, Bastnaesite(Y) $Y(CO_3)F$, Calcio-ancylyte(Ce) $(Ca,Sr)Ce_3(CO_3)_4(OH)_3.H_2O$, Calcio-ancylyte(Nd) $Ca(Nd,Ce,Gd,Y)_3(CO_3)_4(OH)_3.H_2O$, Doverite $YCaF(CO_3)_2$, Parisite(Ce) $Ca(Ce,La)_2(CO_3)_3F_2$, Parisite(Nd) $Ca(Nd,Ce)_2(CO_3)_3F_2$, Synchysite(Ce) $Ca(Ce,La)(CO_3)_2F$, Synchysite(Nd) $Ca(Nd,La)(CO_3)_2F$, Synchysite(Y) (doverite) $Ca(Y,Ce)(CO_3)_2F$. Rare earth halide minerals: Fluocerite(Ce) $(Ce,La)F_3$, Fluocerite(La) $(La,Ce)F_3$, Fluorite $(Ca,REE)F_2$, Gagarinite(Y) $NaCaY(F,Cl)_6$, Pyrochlore $(Ca,Na,REE)_2Nb_2O_6(OH,F)$, Yttrofluorite $(Ca,Y)F_2$. Rare earth oxide minerals: Anatase

(Ti,REE)O₂, Brannerite (U,Ca,Y,Ce)(Ti, Fe)₂O₆, Cerianite(Ce) (Ce⁴⁺,Th)O₂, Euxenite(Y) (Y,Ca,Ce,U,Th)(Nb,Ta,Ti)₂O₆, Fergusonite(Ce) (Ce, La,Y)NbO₄, Fergusonite(Nd) (Nd,Ce)(Nb,Ti)O₄, Fergusonite(Y) YNbO₄, Loparite(Ce) (Ce,Na,Ca)(Ti,Nb)O₃, Perovskite (Ca, REE)TiO₃, Samarskite (REE,Fe²⁺,Fe³⁺,U,Th,Ca)(Nb,Ta,Ti)O₄, Uraninite (U,Th,Ce)O₂. Rare earth phosphate minerals include Britholite(Ce) (Ce,Ca)₃(SiO₄,PO₄)₃(OH,F), Britholite(Y) (Y,Ca)₃(SiO₄,PO₄)₃(OH,F), Brockite (Ca,Th,Ce)(PO₄).H₂O, Chevkinite(Ce) (Ca,Ce,Th)₄(Fe²⁺,Mg)₂(Ti,Fe³⁺)₃Si₄O₂₂, Churchite(Y) YPO₄.H₂O, Crandallite CaAl₃(PO₄)₂(OH)₅.H₂O, Florencite(Ce) CeAl₃(PO₄)₂(OH)₆, Florencite(La) (La,Ce)Al₃(PO₄)₂(OH)₆, Florencite(Nd) (Nd,Ce)Al₃(PO₄)₂(OH)₆, Fluorapatite (Ca,Ce)₅(PO₄)₃F, Gorceixite (Ba,REE)Al₃[(PO₄)₂(OH)₃].H₂O, Goyazite SrAl₃(PO₄)₂(OH)₅.H₂O, Monazite(Ce) (Ce,La,Nd,Th)PO₄, Monazite(La) (La,Ce,Nd,Th)PO₄, Monazite(Nd) (Nd,Ce,La,Th)PO₄, Rhabdophane(Ce) (Ce,La)PO₄.H₂O, Rhabdophane(La) (La,Ce)PO₄.H₂O, Rhabdophane(Nd) (Nd,Ce,La)PO₄.H₂O, Vitusite(Ce) Na₃(Ce,La,Nd)(PO₄)₂, Xenotime(Y) YPO₄. Silicate minerals containing rare earths include: Allanite(Ce) (Ce,Ca,Y)₂(Al,Fe²⁺,Fe³⁺)₃(SiO₄)₃(OH), Allanite(Y) (Y,Ce,Ca)₂(Al,Fe³⁺)₃(SiO₄)₃(OH), Cerite(Ce) Ce₉Fe³⁺(SiO₂)₆[(SiO₃)(OH)](OH)₃, Cheralite(Ce) (Ca,Ce,Th)(P,Si)O₄, Eudialyte Na₄(Ca,Ce)₂(Fe²⁺,Mn²⁺,Y)ZrSi₈O₂₂(OH,Cl)₂, Gadolinite(Ce) (Ce,La,Nd,Y)₂Fe²⁺Be₂Si₂O₁₀, Gadolinite(Y) Y₂Fe²⁺Be₂Si₂O₁₀, Gerenite(Y) (Ca,Na)₂(Y,REE)₃Si₆O₁₈.2H₂O, Hingganite(Ce) (Ce,Y)₂Be₂Si₂O₈(OH)₂, Hingganite(Y) (Y,Yb,Er)₂Be₂Si₂O₈(OH)₂, Hingganite(Yb) (Yb,Y)₂Be₂Si₂O₈(OH)₂, Iimoriite(Y) Y₂(SiO₄)(CO₃), Kainosite(Y) Ca₂(Y,Ce)₂Si₄O₁₂(CO₃).H₂O, Rinkite (rinkolite) (Ca,Ce)₄Na(Na,Ca)₂Ti(Si₂O₇)₂F₂(O,F)₂, Sphene(titanite) (Ca,REE)TiSiO₅, Steenstrupine(Ce) Na₁₄Ce₆Mn₂Fe₂(Zr,Th)(Si₆O₁₈)₂(PO₄)₇.3H₂O, Thalenite(Y) Y₃Si₃O₁₀(F,OH), Zircon (Zr,REE)SiO₄, Thorite (Th,U)SiO₄. Among rare-earth minerals, bastnaesite, monazite, and xenotime are the three most commonly mined REE-bearing minerals (Jordens, 2013).

Vietnam has significant rare-earth potential. Vietnam's rare earth reserves are mainly in primary and weathered deposits (accounting for up to 99% of total reserves), with a small remainder in continental and coastal placer deposits. To date, five primary ore deposits have been discovered, along with numerous continental and coastal placer deposits containing rare earths, mainly light rare earths. The total estimated reserves are approximately 3.5 million tonnes of REO, ranking among the top 10 worldwide. The rare earth resources in Vietnam are in individual deposits, including the North Nam Xe rare earth mine, which contains *bastnaesite*, *parisite*, *lanthanite*, *orthosite*, *cordierite*, *fluocerite*, *sinkirite*, *mariniakit*, *monazite*, *xenotime*, and *uranokite*. Weathered ores have a REO content of 2–16.8%, while the parent ore has a REO content of 0.6–31.35%. The Dong Pao rare-earth mine (*bastnaesite*, *parisite*, *lanthanite*, *orthite*, *barite*, *fluorite*) has an REO content of 0.5–39%. The South Nam Xe rare-earth mine (*parisite*, *bastnaesite*, *lanthanite*) has an REO content of 0.5–36.0%. The Muong Hum rare earth mine (*monazite*, *bastnaesite*, *samaraskite*, *rhabdophane*, *cerianite*, *euxenite*, *thorite*, *zircon*) has an REO content of 1.0–3.18%. The Yen Phu rare earth mine (*fergusonite*, *xenotime*, *monazite*, *samaraskite*, *allanite*, *thalenite*, *cheralite*, *rhabdophane*) has a REO content of 0.1–7.0%. The Pom Lau monazite mine, Ban Gio monazite mine, and Chau Binh monazite mine contain mainly *monazite*, *xenotime*, and *allanite* minerals. The Cat Khanh, Dezi, My Tho, Ke Sung, Cam Hoa, Quang Ngan, Cua Dai, Hon Gom, Vinh My, Ky Ninh, Tuy Phong, and Xuan Thinh monazite mines contain mainly *monazite* and *xenotime* minerals (Nhu, 2021).

Although rare earth elements are highly valuable in modern industries and are relatively abundant, the technology for mineral processing and preparation of rare earths in Vietnam

remains very rudimentary, mainly at the laboratory/pilot scale. Previous research on rare earth ore beneficiation is presented here for overview and analysis.

3. Research in rare earth ore beneficiation technology in Vietnam

In general, beneficiation technology is a combination of methods (depending on the characteristics of the main mineral and associated minerals): (1) Gravity separation - magnetic separation – flotation; (2) Gravity separation; (3) Magnetic separation - gravity separation; (4) Flotation; (5) Gravity separation – flotation. Several studies on ore beneficiation technology at the Nam Xe, Dong Pao, Yen Phu mines, and some marine placer mines have been conducted to propose ore beneficiation methods.

For the rare-earth ore at North Nam Xe, the main mineral is bastnaesite, with a content of 5-7%. The gangues are quartz, barite, illite, kaolinite, chlorite, feldspar, etc. Run-of-mine ore has an average content of ~1.2% REO, ~33% Fe, and ~40% SiO₂. In 1971, the Institute of Non-ferrous Metallurgy researched and enriched the initial sample from 14.8% REO in magnetic concentrate to 19.5% REO and from 14.8% REO in flotation concentrate to 18.5% REO. In 2013, the Institute of Mining and Metallurgy Science and Technology researched an initial sample containing 4.6% REO. Flotation technology was used, yielding a rare earth concentrate with 30% REO and a recovery rate of 63.56%. The flowsheet of beneficiation technology is shown in Figure 1 (Nhu, 2021; Hien 2013).

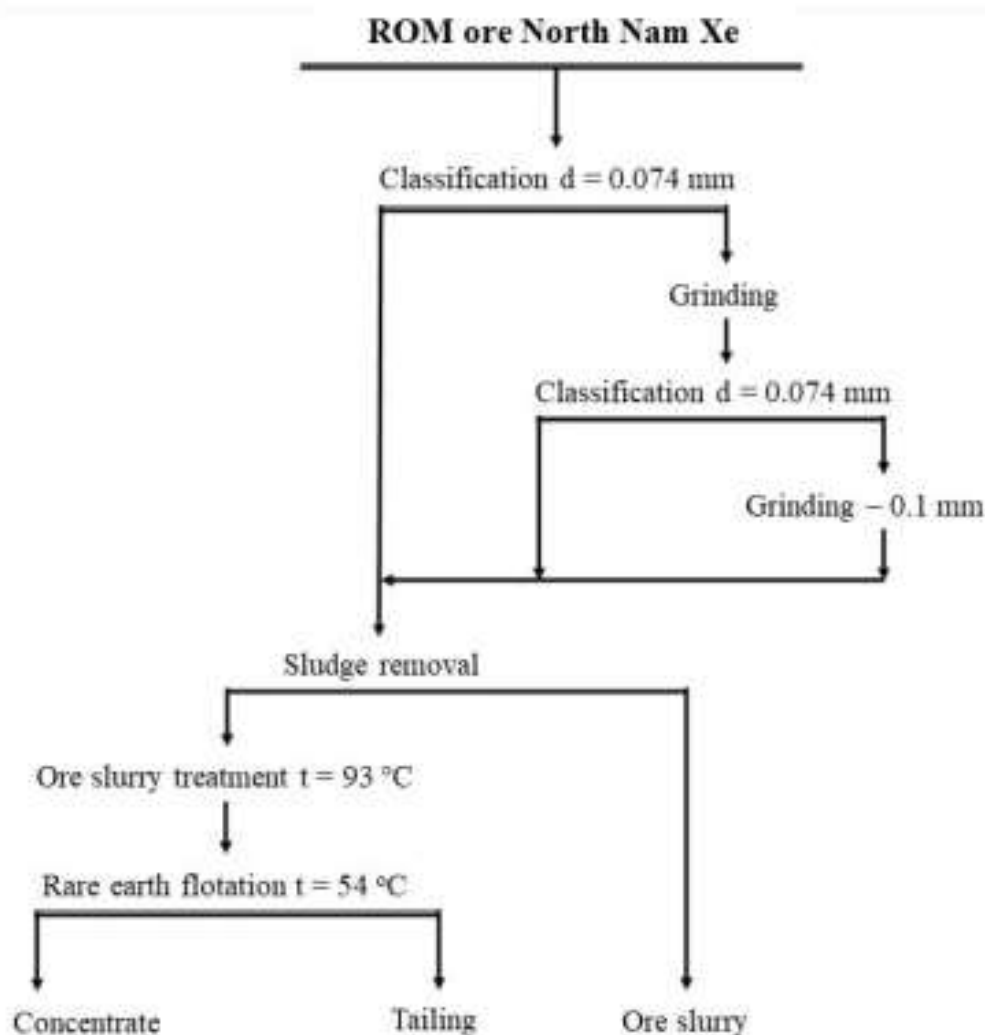


Figure 1. The experimental flowsheet of the rare earth ore in the North Nam Xe beneficiation (Hien, 2013)

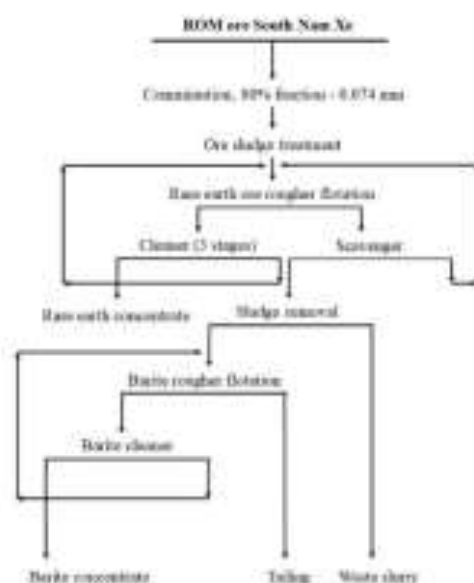


Figure 2. The Mountrin Pass's flowsheet technology (Minh, 1984)

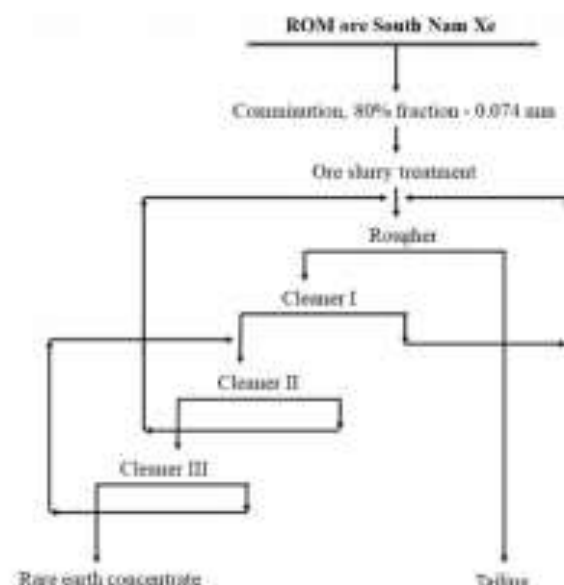


Figure 3. Robert Möckel's flowsheet technology (Robert, 2019)

For the South Nam Xe rare-earth deposit: According to Fong-Sam (2013), rare-earth elements are present as calciocarbonatites (0.34-0.61%) and ferrocarnatites (4.32-16.3%). Rare earth-containing minerals include parisite, bastnaesite, and synchysite. Accompanying minerals include baryte, celestine, calcite, biotite, and magnetite (Fong-Sam, 2013). The initial sample had a REO content of 7-10% and fine contamination with accompanying minerals. Mountrin Pass and Robert Möckel introduced the beneficiation. In Mountrin Pass's circuit, the technology is direct flotation with chemicals, sodium, NaF, dextrin, and liquid glass. The flotation results yielded a concentrate with 30-35% REO at a recovery rate of 80-85%. Barite concentrate was also recovered, but the REO content here was still high (7%) (Hanh, 1988). In Robert Möckel's research, the technology includes rougher flotation, scavenger stages, crushing, 3 cleaner stages, and 1 scavenger for concentrate 1. The REO content reached 40% (Robert, 2019). The flowsheet technology is shown in Figure 2 and Figure 3.

For the Yen Phu rare earth ore, the reserves are 28,000 tonnes of REO, with the main mineral being Xenotime. The iron-containing minerals are goethite (18-20%) and magnetite (24-26%). The other minerals are quartz 41-43%, kaolinite + chlorite 3-5%, feldspar 2-4%, talc 1-3%, etc. The ore has an average REO content of ~1.2%, ~33% Fe, and ~40% SiO₂ (Khang, 2012). The proposal beneficiation technology are (1) gravity separation, including washing and classification of ore; (2) magnetic separation for the recovery of iron concentrate; (3) flotation for the recovery of rare earth concentrates using soda flotation reagents (pH = 9); liquid glass, lignin, and corn starch as depressant reagents; berol and diesel oil as collectors. Rare-earth-concentrated ore has a recoverable yield of 40%, and the tailings contain 0.7% REO. The flowsheet for Yen Phu rare-earth ore beneficiation technology is shown in Figure 4 (Phong, 2020).

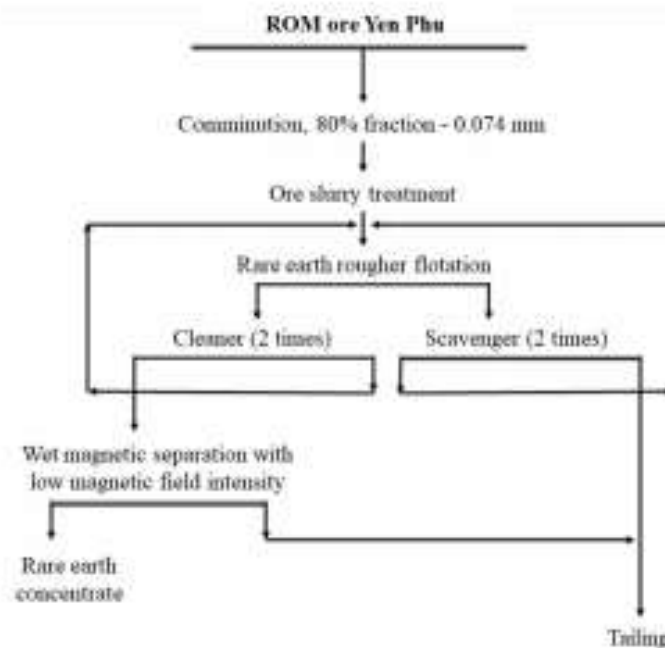


Figure 4. The flowsheet for Yen Phu rare-earth ore beneficiation technology (Dung, 2020)

For the Dong Pao rare-earth ore, the main mineral is Bastnaesite. A small amount of REE exists as yttrifluorite and fluorite. The beneficiation technology combines comminution (trommel screening, crushing, grinding, and classification), gravity separation (shaking table/multi-gravity separator), magnetic separation, and flotation. The ore has an average content of ~5.98% REO, 21.58% BaSO₄, and 12.35% CaF₂. The flowsheet technology was shown in Figure 5 (Su, 2014).

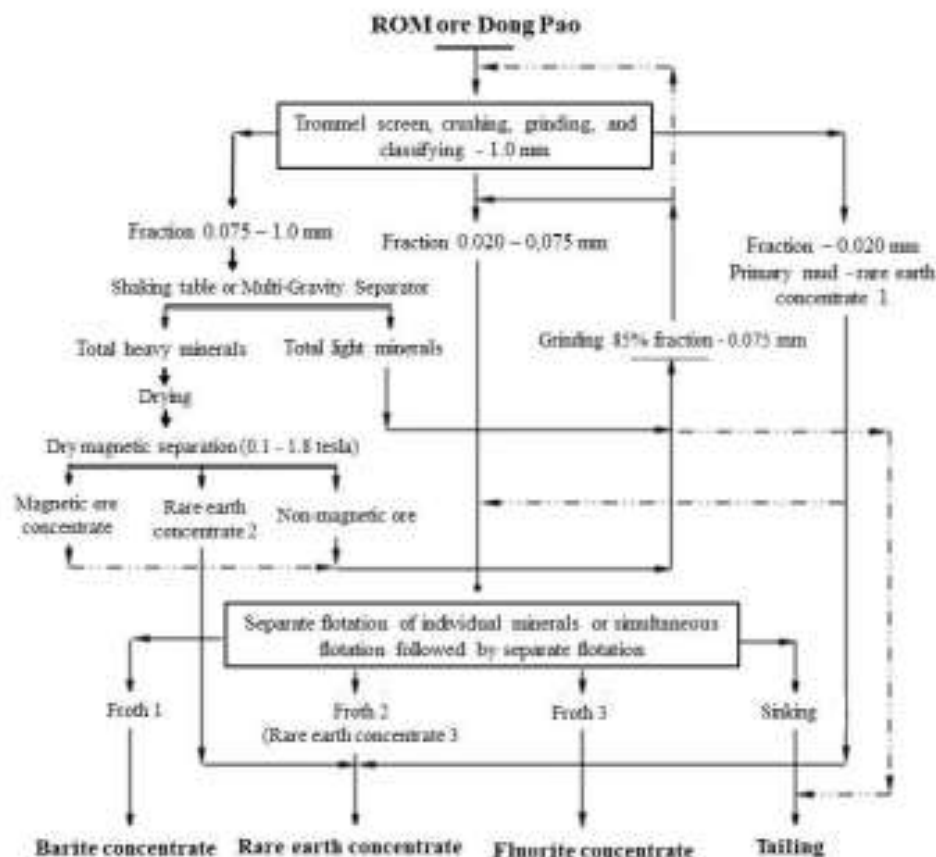


Figure 5. The flowsheet for Dong Pao rare-earth ore beneficiation technology (Dung, 2020)

Another research on Dong Pao's rare-earth flotation flowsheet is a proposal for a cooperation project with the Federal Republic of Germany. Accordingly, the flotation results yielded a total rare-earth concentrate content of 30.34% REO at a recovery rate of 66.75%. The barite concentrate has a content of 86.50% at a recovery 90.44%, and the Fluorite concentrate has a content of 39.10% at a recovery of 59.48%. The technology flow sheet is shown in Figure 6 (Nhu, 2021).

The Dong Pao's rare-earth ore was sent to the Lakefield Research Laboratory in Ontario, Canada (Gupta, 2005). The ore was studied in three ways: (1) Direct flotation, concentrated flotation recovered bastnasite mineral with REO content reaching 6.76% at a recovery rate of 45.40%. Flotation results are shown in Table 3; (2) Selective flotation of CaF_2 - BaSO_4 - REO with REO content reaching 34.3% and a recovery rate of 57.6%; (3) Selective flotation of BaSO_4 - CaF_2 - REO with the REO content of 30.6%, with a yield of 67.1% (Nhu, 2021).

Several studies from other partners and experts were also conducted, such as (1) Sumitomo Metal Mining Company (Japan) used a Barite-Fluorite-Rare Earth flotation stage, yielding a concentrate content of 45.9- 48.4% and a recovery rate of 75.6 - 76.1%; (2) Dr. Pham Van Hanh used selective grinding, mechanical classification, and magnetic separation. The concentrate had a REO content of 31.77% with a recovery rate of 84.46%. In addition, the study also showed the possibility of separating barite and fluorite by flotation using fatty acids and alkyl sulfates; Duong Van Su used a combination of magnetic separation and flotation. The rare earth concentrate had a REO content of 31.66% with a recovery rate of 63.52%. However, the study did not address the recovery of barite and fluorite from the F7 ore body (Nhu, 2021).

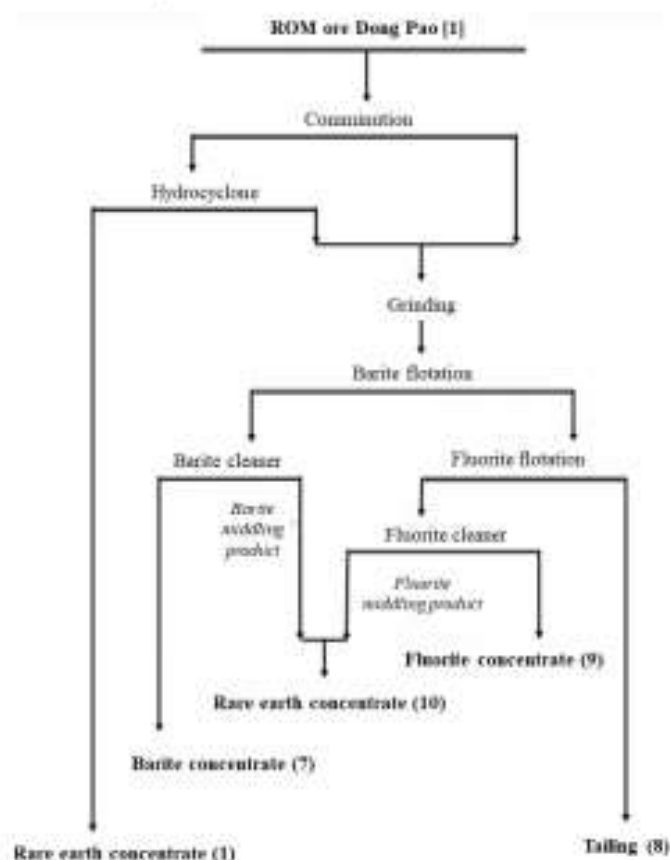


Figure 6. The flowsheet for Dong Pao rare-earth ore beneficiation technology according to the research of the German group

Overall, rare earth ore research in Vietnam utilizes a combination of conventional technologies, with differentiation and breakthroughs stemming from flotation reagent systems and technological flowsheets. Most studies are limited to experimental and pilot scales. The biggest obstacles here are: (1) Research in the field of hydrometallurgy and extraction is still limited; (2) it lacks sufficient conditions to evaluate the feasibility and economic efficiency of the application; (3) issues in the environmental impact after processing and purification.

4. Challenges and opportunities

The demand for rare earth elements is high due to their strategic importance as raw materials in the Fourth Industrial Revolution. Currently, Vietnam is strengthening cooperation with major global corporations to develop the semiconductor, AI, and artificial intelligence industries.

With strong support from the major Party, State, Government, and Ministries, Departments, and Agencies policies, and businesses willing to collaborate, we can make breakthroughs in processing and efficiently using rare earth elements. Otherwise, Vietnam has many outstanding institutions that are leaders in geology, mining, mineral processing, and metallurgy, with the potential to develop and implement strategic national technologies.

The challenges in the development of rare earth industries in Vietnam can be listed:

- The reserves are relatively large, approximately 3,500,000 tonnes of REO, but they are unevenly distributed and have a complex composition, mainly consisting of "light" elements;
- The mining situation remains relatively modest;
- The concentrate after beneficiation has a low REO content and recovery rate. The tailings still contain a significant amount of REO. Most beneficiation results are limited to experimental and pilot scales;
- The main technology under research is hydrometallurgy; however, separating pregnant leach solution and purifying individual rare earth oxides are not yet feasible;
- The chemicals used for the extraction and separation of rare earth elements remain classified and proprietary to a few countries. Vietnam has not yet mastered these technologies.

In addition, there are also great opportunities for the development of the rare earth industry as well as innovating the technology related to rare earth in Vietnam:

- Specific assessments of rare earth resources, the material composition of ore deposits, by-products from processing, tailings ponds, etc., can be carried out;
- Research on mining technology towards cost optimization, selective ore extraction, and appropriate rock breaking degree to meet the requirements of subsequent processing stages. Planning of waste disposal sites for reuse when processing technology reaches a sufficiently high level;
- Implementation includes: optimizing existing ore processing technology, applying modern technologies and equipment to ore processing, conducting pilot production, and advancing towards industrial-scale ore processing. Rare earths in tailing ponds should be recovered using microbial leaching technology;
- Research and development of technologies for separating individual rare earth oxides, pairs of individual rare earth oxides, and refining the resulting products.

5. Conclusion

Vietnam has considerable rare earth resources, but rare earth processing in our country remains very rudimentary, currently at the laboratory or pilot scales. It is necessary to have systems, equipment, and technological solutions for mineral beneficiation, extraction, and purification of these minerals.

Research on rare earth ore beneficiation has focused primarily on the most important minerals: bastnasite, monazite, and xenotime.

The main methods for recovering minerals from rare-earth ores are gravity separation, magnetic separation, electrostatic separation, and flotation.

The research flowsheet for the beneficiation of ore from North Nam Xe and South Nam Xe purely uses the flotation method. For the Dong Pao ore, a combined gravity separation, magnetic separation, and flotation flowsheet is used. The technological flowsheet for the beneficiation of rare earth ore from Yen Phu combines flotation and magnetic separation.

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