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A Detailed Review on the Recovery of Rare Earth Oxide from NDFEB Magnet using Natural Deep Eutectic Solvents, efficiency of Leaching with Different Parameters

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ABSTRACT

This research explores the use of a Natural Deep Eutectic Solvent (NADES) made from glycine and lactic acid for selectively extracting neodymium (Nd) from NdFeB magnets, commonly found in electronic devices like hard drives, motors, and wind turbines. With the rising demand for rare earth elements, developing sustainable and eco-friendly recycling techniques for recovering these valuable materials from discarded products is becoming increasingly crucial. Traditional leaching approaches typically use strong mineral acids, which present environmental and safety concerns because of their corrosive nature and the hazardous waste they generate.

Natural deep eutectic solvents (NADES) have become a promising type of environmentally friendly solvent, offering multiple benefits compared to conventional solvents. They are generally made from naturally sourced, biodegradable, and non-toxic materials, and can be easily produced through straightforward mixing and heating methods. In this study, the NADES system composed of glycine and lactic acid combines glycine's ability to chelate, as an amino acid, with the acidic properties of lactic acid, allowing for effective dissolution and complexation of neodymium ions.

The leaching process was optimized by examining key operational factors such as temperature, leaching duration, and the solid-to-liquid (S/L) ratio. The highest recovery rate of neodymium, around 73%, was obtained under mild conditions: 60 °C, a leaching time of 3 hours, and an S/L ratio of 1:20. These findings demonstrate the NADES system's efficiency with relatively low energy consumption, highlighting its practical potential. It was also observed that higher temperatures reduced leaching efficiency, likely because of thermal degradation of the solvent components, which affects their chemical stability and ability to bind metals.
Spectrophotometric analysis revealed that the best absorbance peak for measuring neodymium concentration is at 660 nm within the visible spectrum. This specific wavelength was utilized to monitor the dissolution of neodymium during the leaching process and to determine recovery yields. Further experiments using other organic acids like citric, malonic, and acetic acid resulted in lower recovery rates, highlighting the superior effectiveness and synergistic effect of the glycine–lactic acid system.

In summary, this study shows that the glycine–lactic acid NADES is an efficient, sustainable, and environmentally friendly option for recovering neodymium from magnet waste. This method shows great potential for scaling up and being incorporated into wider e-waste recycling initiatives aimed at decreasing dependence on primary rare earth mining

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1.INTRODUCTION

1.1 RARE EARTH ELEMENT

Rare earth elements (REEs) are a set of 17 visually indistinguishable heavy metals. They exist in minute quantities, are elusive, and are difficult to mine and extract. Yet, these elements play a significant role in the manufacture of many high-tech devices used in consumer products, industrial electronics, and defence systems. These factors put REE at the centre of significant geopolitical manoeuvring.[1].

Rare Earth Element	Primary Mining Locations	Abundance	Common Applications
Cerium	China, Brazil, India	66	Self-cleaning ovens, automotive catalytic converters, glass polishing
Dysprosium	China, USA, Australia	5.2	Nuclear reactor control rods, high-intensity lighting, magnets
Erbium	China, USA, Russia	3.5	Fiber optic telecommunications, lasers
Europium	China, USA, Brazil	2	Color TV screens, phosphors, lasers
Gadolinium	China, USA, Russia	6.2	MRI contrast agents, high refractive index glass
Holmium	China, USA, Brazil	1.3	Strongest known magnetic pole, used in control rods in nuclear reactors
Lanthanum	China, USA, Australia	39	Camera lenses, rechargeable batteries, catalysts
Lutetium	China, USA, Australia	0.8	Petroleum refining catalysts, LED lights
Neodymium	China, Australia, USA	41	High-strength magnets, hard drives, microphones
Praseodymium	China, USA, Russia	9.2	Magnets for electric vehicle motors, wind turbines
Promethium	Not naturally mined (synthetic)	-	Nuclear batteries, beta radiation sources
Samarium	China, Russia, USA	7.1	High-temperature magnets, lasers, masers
Terbium	China, USA, Australia	1.2	Solid-state devices, magneto-optic recording systems
Thulium	China, USA, Brazil	0.5	Portable X-ray devices, lasers
Ytterbium	China, USA, India	3.1	Portable X-ray machines, fiber amplifiers in telecommunications

1.2 APPLICATION OF RARE EARTH ELEMENT

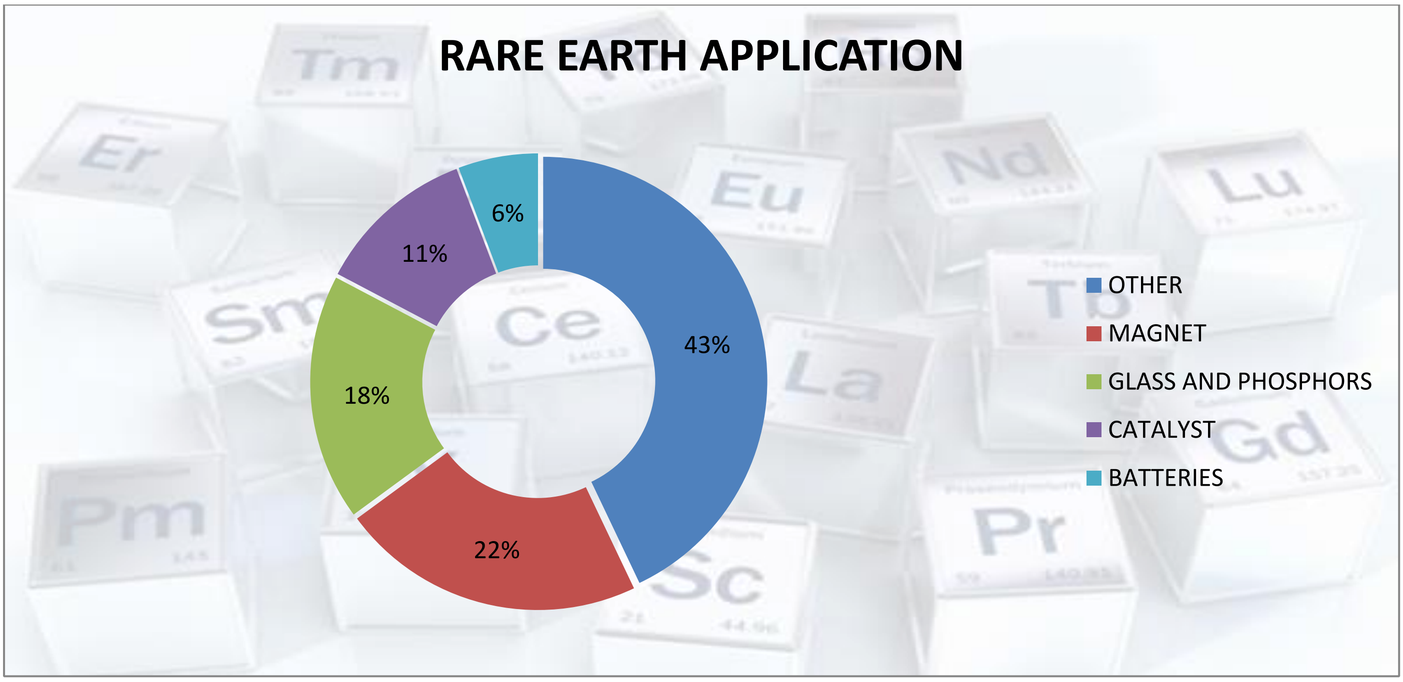

Figure 1

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2.LITERATURE REVIEW

Chemistry and Properties of Deep Eutectic Solvents (DESs)

Deep eutectic solvents (DESs) are gaining attention as a versatile and more sustainable class of solvents, particularly for recovering rare earth elements (REEs) from secondary materials such as NdFeB magnets. Generally, DESs are prepared by combining two or more components—typically a hydrogen bond acceptor (HBA) such as choline chloride and a hydrogen bond donor (HBD) such as urea, glycerol, or organic acids—followed by mixing them in specific molar ratios. This mixture forms a eutectic system with a melting point that is much lower than that of the individual components, which enables the resulting mixture to stay as a stable liquid at, or near, room temperature[2] .

This behavior is mainly driven by the strong hydrogen-bonding network created between the HBA and HBD. These interactions disturb the original crystal structures of the components, producing melting point depression. As a consequence, DESs can be tuned to achieve desirable physicochemical properties, including viscosity, polarity, acidity, and conductivity. In addition, this structural arrangement supports the dissolution of a wide variety of metal salts and oxides, REE compounds included [6].

Relative to ionic liquids (ILs), DESs present several benefits. They are typically simpler and more cost-effective to produce, and they are often made using biodegradable and comparatively non-toxic materials, which improves their environmental compatibility. They also tend to have lower volatility and reduced flammability compared with ILs, thereby cutting down on potential emissions and strengthening process safety [4]These advantages explain why DESs are especially attractive for large-scale industrial applications in metal recovery.

Another important aspect is that DESs can be designed to provide selective extraction performance. By changing the choice of HBA and HBD components and adjusting their molar ratios, researchers can tailor key solvent parameters such as acidity, coordination ability, and viscosity, with the aim of improving leaching efficiency and selectivity toward specific metals. For instance, acidic DESs based on choline chloride and organic acids (for example malonic or lactic acid) have been shown to enhance the release of REEs from NdFeB magnet waste. This effect is linked to stronger metal complexation and improved dissolution [5]

Moreover, DESs can be engineered for dual functionality, where they act not only as leaching agents but also as extractants during later separation steps. This multifunctional role lowers the need for additional chemicals and helps streamline the recycling process, thereby supporting sustainability in a broader sense (Alguacil & Robla, 2023). Even so, some obstacles still need attention. High viscosity and the potential degradation of the solvent under certain conditions highlight the need for continued research to optimize DES formulations for practical use.

Mechanisms of REE Leaching Using DESs

To optimize the recovery of rare earth elements, it is important to understand how deep eutectic solvents (DESs) dissolve them and why they extract them selectively. When REEs are leached from NdFeB magnets using DESs, the process involves several intricate interactions between metal ions and components of the solvent. These interactions are mainly guided by coordination chemistry and acid–base reactions.

In DESs, metal ions are generally released through complexation with chloride ions and hydrogen bond donors that are present in the solvent. Chloride ions can act as ligands, binding to REE ions and forming stable chloro-complexes. This, in turn, increases the solubility of the rare earth elements (Yadav et al., 2025). At the same time, organic acids or urea molecules within the DES may interact with metal ions through hydrogen bonding or chelation, which helps further stabilize the dissolved species.

Density Functional Theory (DFT) and other computational methods have been used to gain a clearer picture of these interactions at the molecular level. For example, DFT studies show that the chloride ions and hydrogen bond donors in DESs form a favorable coordination environment for REEs. This lowers the energy barrier for metal dissolution. As a result, these interactions help explain why DESs show strong selectivity for REEs compared with transition metals such as iron, which are less likely to form stable complexes (Yadav et al., 2025).

The acidity of the DES also has a major impact on the leaching mechanism. In more acidic DESs, metal oxides on the magnet surface can be protonated, which promotes the breakdown of the magnet matrix and releases REEs into the solvent. However, the acidity must be carefully balanced. If conditions become too acidic, base metals may dissolve alongside the REEs, lowering selectivity and making later separation more difficult [5]

Temperature plays a key role as well. Higher temperatures improve reaction kinetics and reduce solvent viscosity, which enhances the mass transfer of metal ions. By applying these mechanistic insights, multi-stage leaching strategies can achieve better recovery efficiencies and higher purities [2]

Pretreatment Methods for Secondary NdFeB Magnet Recovery**

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Pretreating NdFeB magnet waste is an essential step for enhancing rare earth element recovery. It improves the likelihood that REE-bearing phases become accessible to DES leaching. As a result, mechanical, thermal, and chemical pretreatment routes have all been investigated to raise recovery yields.

Mechanical pretreatment—such as grinding, milling, or shredding—reduces the size of magnet particles, thereby increasing the specific surface area exposed to the solvent. This kind of disruption brings REE-enriched grain boundaries and phases closer to the leaching medium, so dissolution can occur more rapidly and more thoroughly (Heo et al., 2024). 6However, if milling is carried out too aggressively, it may cause particle agglomeration or diminish magnetic properties, which means the treatment intensity needs to be optimized for efficient processing.

Thermal pretreatment involves heating the magnet waste so that phase transformations, oxidation, or hydrogen decrepitation can take place. Annealing or oxidation treatments convert metallic constituents into oxides, which are often easier to dissolve in acidic DES systems. Hydrogen decrepitation—driven by hydrogen absorption and the resulting expansion that breaks the magnet apart—is particularly effective for increasing porosity and improving leachability (Yadav et al., 2025).

Chemical pretreatments, including acid washing or carefully controlled oxidation, can remove surface contaminants or passivate selected phases. In doing so, they can selectively improve the availability of REEs for leaching. For example, mild acid washing can remove surface iron oxides that would otherwise interfere with the leaching process (Heo et al., 2024).

In practice, combining pretreatment methods can create synergistic effects that enhance both the efficiency and selectivity of DES leaching. At the same time, process parameters must be tuned carefully to ensure that pretreatment does not generate additional secondary waste streams or reduce solvent performance (Alguacil, 2024).

Environmental and Economic Considerations

The use of DES-based approaches for rare earth recovery depends not only on technical performance, but also on whether the process can remain environmentally and economically sustainable. Life cycle assessments (LCAs) of DES processes point to meaningful reductions in greenhouse gas emissions, energy demand, and hazardous waste generation relative to conventional acid leaching. This advantage is closely linked to the comparatively benign character of DESs and their potential for recycling (Alguacil, 2024).

Environmental studies on toxicity and biodegradability also support these findings. Overall, DESs tend to show low ecotoxicity and good biodegradability, largely because many are built from natural or bio-based components such as choline chloride and organic acids (Deng et al., 2025). Even so, the behavior of DES constituents over multiple recycling cycles, as well as the possible build-up of impurities, still needs further evaluation to prevent environmental drawbacks.

Economically, DESs may offer cost benefits compared with ionic liquids and strong mineral acids, particularly when raw materials are inexpensive and solvent preparation is straightforward. Nonetheless, several barriers must be addressed when scaling up recovery processes. These include solvent regeneration, the handling of viscous liquids, and how well the DES leaching step integrates with subsequent purification stages. Capital and operating costs therefore need to be reviewed carefully for pilot-scale and industrial deployments to confirm competitiveness (Yadav et al., 2025).

Finally, policy initiatives that encourage circular economy practices and critical materials recycling can help create market pull and regulatory support for DES technologies. Measures that reward low-carbon and sustainable processing could further accelerate adoption in industries that depend on rare earth magnets (Alguacil & Robla, 2023).

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3. MINING PROBLEMS

REEs are unimpressive looking they exist as a lustrous silvery-white soft powder but turn to a dull, gravy colour when exposed to air. Rare earth minerals are mainly found in Australia (particularly in Western Australia), Brazil (across several regions including Amazonas), China, India (in the states of Andhra Pradesh and Tamil Nadu), Russia (with significant deposits in the Kola Peninsula and Siberia), and the United States (particularly in California and Wyoming). China is, by far, the largest producer of rare earths with vast reserves in Inner Mongolia and Sichuan. China accounts for about 97% of the world's production of rare earths.

Finding rare earth elements is difficult enough; extracting them and converting them to a usable form presents more challenges. Refining REEs is energy-intensive, requiring elevated temperatures and multiple stages of processing. REEs are chemically similar and often occur together in the same mineral deposits, which makes separating them a technically challenging and expensive process. Mining involves large-scale operations that produce significant amounts of rock waste, while the subsequent extraction requires hydrometallurgical processes that involve dangerous chemicals and produce toxic waste and radioactive by-products. These processes disrupt ecosystems and can cause soil, water, and air pollutions. Recycling REE from spent devices is also very difficult, environmentally impactful, and expensive.[2]

These factors make the barriers to entry into the REE mining industry very high

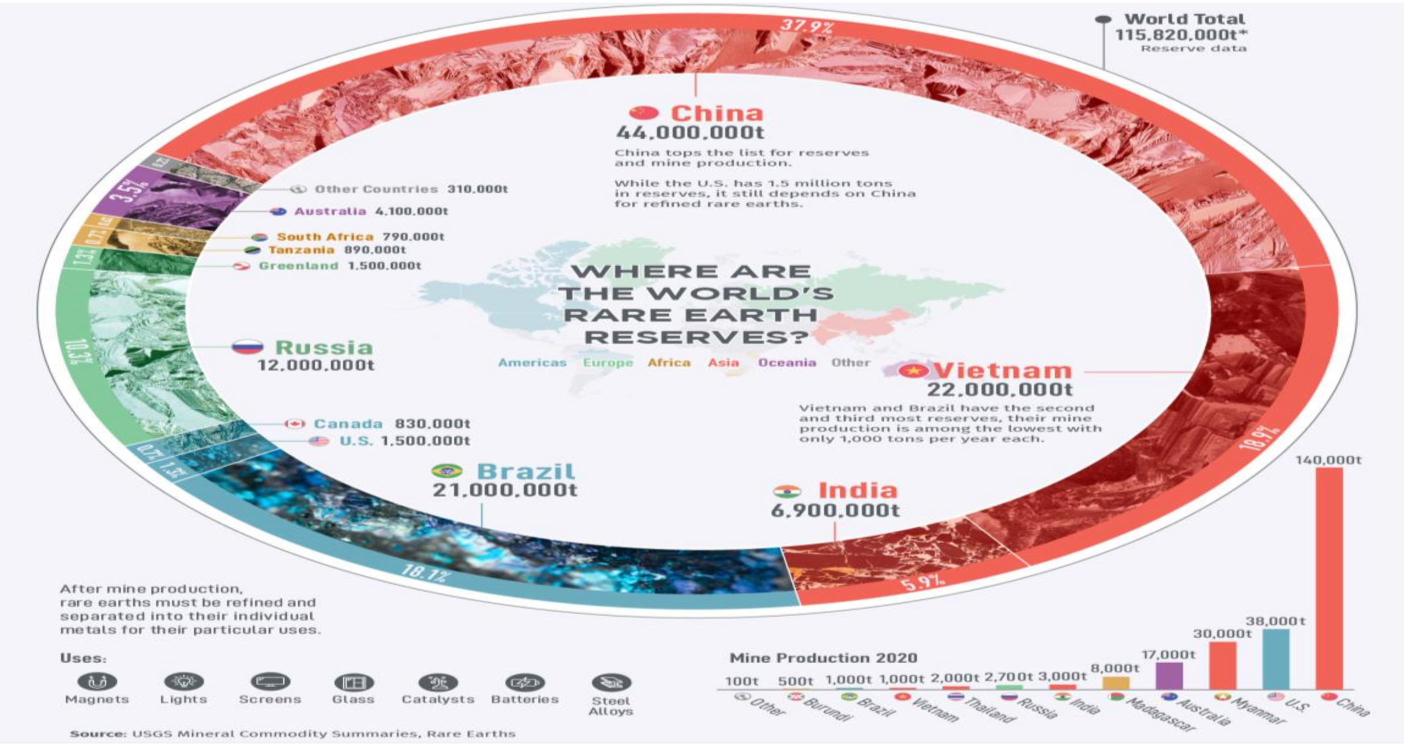

Figure 2

3.1 SECONDARY SOURCE OF REE

REE deposits are located in China, Australia, the United States, Brazil, and Russia. Although reactivation mines can contribute to maintaining the supply, mining generates waste and often yields low concentrations of REEs. In contrast, secondary sources, such as electronic waste (e-waste), promote the circular economy by enabling the recycling and reuse of materials. Recycling contributes to both securing the REE supply and minimizing environmental impacts.LEDs, headphones, smartphones, hard disk drives (HDDs), and rechargeable batteries represent viable secondary REE sources. These e-wastes can contain higher REE concentrations than some natural minerals, making them significant candidates for recovery efforts. The recovery of REEs from secondary sources can be carried out via pyro metallurgical and hydrometallurgical processes, often combined to optimize performance.Pyrometallurgy employs high temperatures (1000 °C),[1] while hydrometallurgy operates at room temperature (25 °C),

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reducing harmful gas emissions. Hydrometallurgical routes involve acid or alkaline leaching, as well as purification techniques: precipitation, solvent extraction (SX), ion exchange, and membranes.

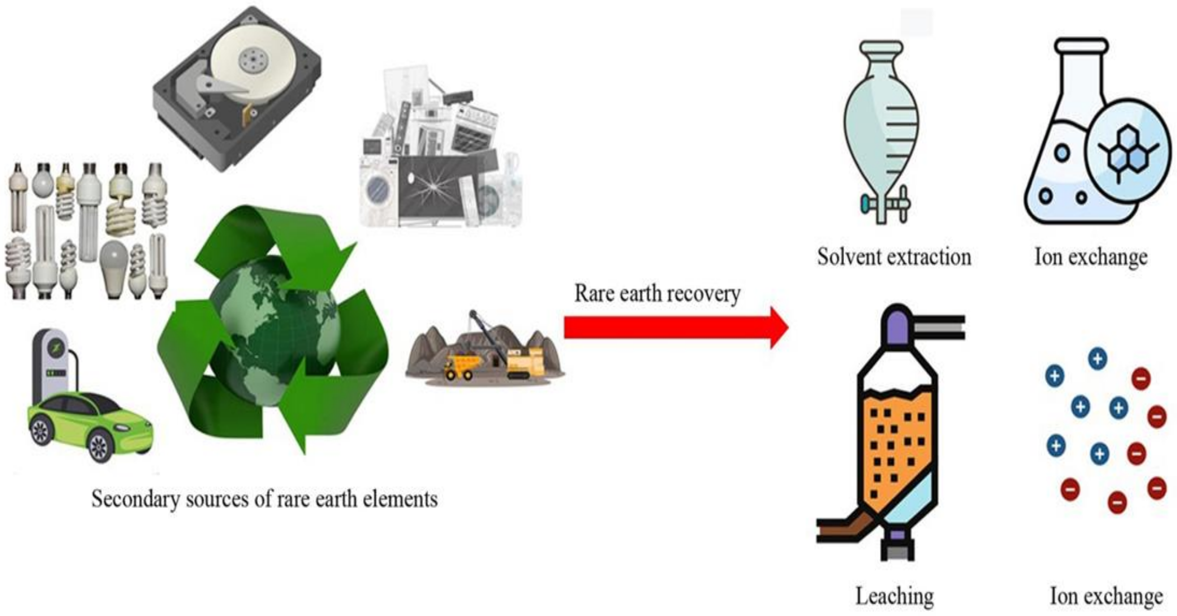

Figure 3

4 HYDROMETALLURGY

Hydrometallurgical methods of recycling were developed because of their low energy consumption in contrast to pyro metallurgical methods, where high temperatures are needed to melt the alloys. However, hydrometallurgical methods can also have some drawbacks, such as large waste generation and usage of no environmentally friendly chemicals. The methods provide excellent extraction properties and good separation factors between the REEs and other impurities, if the correct chemicals are selected. Numerous studies have been performed to determine the ideal reagents and experimental conditions for the treatment of most REEs. Hydrometallurgical processes normally consist of two steps: dissolution of the material/waste and separation of the elements using solvent extraction or ion-exchange. Dissolution is usually performed by leaching the metals using acids of varying concentrations. The acids most used and developed for magnet recycling are Hall, H_2SO_4, and HNO_3. These have been examined for decades, meaning the criteria affecting the efficiency of the leaching, such as acid concentration, solid/liquid (S/L) ratio, temperature, or even the use of the ultrasonic bath, have been studied in detail . Despite their excellent leaching properties, using strong inorganic acids can have some drawbacks, such as poisonous gas evolution during leaching, adverse impact on the environment, soil acidification (in cases of release), and challenges during handling. Leaching has already been studied using some organic acids, such as acetic acid. Acetic acid has the advantage of being a green solvent, it is easily degradable via aerobic and anaerobic conditions, and has possible regeneration capacities. The literature on leaching of neodymium magnets using organic acids is, however, very scarce and should be studied further in order to determine their potential use for industrial-scale REEs reprocessing.[20]

5.NdFeB MAGNET

NdFeB magnets, also known as Neodymium Iron Boron magnets, "Neo","NIB" magnets or rare earth magnets are permanent magnets made of neodymium, iron & boron. They belong to the rare earth magnet family and have the highest magnetic properties of all permanent magnets, stronger than samarium cobalt (SmCo), alnico and ferrite. Known for their high performance, versatility, and cost-effectiveness, these magnets are a cornerstone of modern technology. They are widely used in industries such as electronics, automotive, renewable energy, and medical devices.

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5.1 COMPOSITION

Neodymium-iron-boron (NdFeB) magnets extracted from mobile phones and hard disk drives were initially classified based on the manufacturing year or production period of the devices, following a previously established categorization scheme. This temporal classification facilitated the identification of trends in the elemental composition of critical rare earth elements (REEs), specifically dysprosium (Dy), neodymium (Nd), and praseodymium (Pr). The compositional analysis, illustrated in Figure 2, demonstrated significant temporal variations: the dysprosium content declined from 1.9% to 0.7%, whereas the concentrations of neodymium and praseodymium increased from 22.0% to 28.3% and from 2.9% to 4.7%, respectively.[19]

The observed reduction in dysprosium usage is particularly noteworthy. Given that nearly the entirety of global dysprosium production is allocated to NdFeB magnet manufacturing, dysprosium is both a critical and scarce resource. Its market price exhibits considerable volatility, largely driven by supply limitations, especially those originating from China. To mitigate these challenges, novel manufacturing techniques have been developed to decrease reliance on heavy rare earth (HRE) elements such as dysprosium, without compromising the magnetic performance of the materials.[3]

Among these innovations, the Grain Boundary Diffusion Process (GBDP) stands out as particularly impactful. This technique enables the targeted incorporation of HRE elements, including dysprosium and terbium (Tb), exclusively at the grain boundaries within the magnet's microstructure. By doing so, GBDP substantially reduces the total dysprosium content required while preserving high coercivity, which is crucial for maintaining thermal stability and magnetic strength.[18] Notably, the remanence, defined as the magnet's capacity to retain magnetization, remains essentially unaffected. Consequently, magnets produced via GBDP are more cost-effective and efficient, thereby enhancing supply chain stability.

The increase in neodymium content over time is attributable to the miniaturization of electronic devices. As mobile phones and hard disk drives become increasingly compact, the magnets incorporated within them must deliver greater magnetic performance despite reduced dimensions. Enhancing neodymium concentration improves coercivity and magnetic field strength, facilitating the production of smaller yet high-performance magnets.

Similarly, praseodymium is frequently introduced as a partial substitute for neodymium, typically in a ratio of approximately 1:5, to reduce costs while maintaining magnetic performance. Due to their analogous chemical properties, neodymium and

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praseodymium are challenging to separate and are therefore commonly utilized together in the form of a Pr/Nd alloy. This close chemical affinity accounts for the correlated variation in their concentrations.

Subsequent to this initial characterization, a second phase of analysis was conducted to ascertain the average elemental composition of NdFeB magnets recovered from mobile phones and hard disk drives, irrespective of their manufacturing periods. rare earth elements (Nd, Pr, and Dy) constitute, on average, 28.8% of the sample mass, whereas iron (Fe) accounts for approximately 61.9% of the mass.

These compositional data provide a robust foundation for assessing recovery strategies employing environmentally benign techniques such as organic acid leaching, as well as advanced extraction methods including ultrasound- and microwave-assisted processes. Such information is vital for the development of sustainable approaches to recover rare earth elements from end-of-life electronic devices, thereby reducing dependence on primary mining activities and promoting the principles of a circular economy.[4]

5.2 WHY RECYCLING OF NdFeB MAGNET IS NECESSARY:

Recycling neodymium-iron-boron (NdFeB) magnets is a vital approach to tackling worldwide sustainability issues, including environmental protection, geopolitical stability, economic efficiency, technological progress, and social fairness. This paper combines various reasons for emphasizing the recycling of NdFeB magnets, backed by data and policy analysis, to highlight its importance in modern resource management strategies.[6]

1. Environmental Necessities

Traditional mining methods for extracting neodymium cause significant environmental damage. These mining activities produce radioactive waste like thorium and acidic runoff that harm land and water ecosystems. Additionally, the large-scale land use required for extracting rare earth elements (REEs) leads to habitat destruction and loss of biodiversity. Recycling NdFeB magnets can reduce about 90% of these environmental impacts by avoiding the need for primary ore extraction. It also cuts energy use by 10 to 15 times compared to mining, supporting global climate goals such as those in the Paris Agreement by significantly lowering greenhouse gas emissions. Disposing of NdFeB magnets in landfills risks contaminating soil and groundwater through heavy metals and REE leaching, which recycling helps prevent.

2. Geopolitical and Supply Chain Factors

The global dependence on neodymium is vulnerable due to over 80% of its production being concentrated in China. This monopoly creates risks like export restrictions, price fluctuations, and political conflicts. Recycling provides a strategic way to diversify supply sources, making supply chains more resilient to disruptions. Furthermore, with rising demand from electric vehicles, wind energy, and electronics, current neodymium reserves may be depleted within 50 years. Recycling prolongs the life of these reserves, giving time to develop sustainable mining methods or find alternative materials.

3. Economic Feasibility and Resource Efficiency

Recycling neodymium achieves recovery rates above 99%, which is much higher than the less than 10% yield from mining raw ore. This efficiency lowers raw material costs for industries using NdFeB magnets, such as automotive and renewable energy sectors, enhancing their economic competitiveness. The global electronic waste stockpile holds an estimated $10 billion worth of untapped rare earth elements, making recycling a profitable opportunity to convert waste into valuable resources. Investing in recycling infrastructure—including collection, sorting, and processing—also creates jobs in emerging green technology fields, promoting economic growth within a circular economy framework.

4. Technological and Industrial Importance

NdFeB magnets are crucial for high-performance uses in clean energy technologies like electric vehicle motors and wind turbine generators, which are key to global decarbonization efforts. Maintaining a reliable neodymium supply through recycling is vital to achieving international net-zero emission goals by 2050. Recycling also complies with regulations such as the European Union’s Critical Raw Materials Act, which requires incorporating recycled materials in manufacturing to reduce waste and encourage circularity.

5. Social and Ethical Aspects

Traditional rare earth element mining often involves unethical labor practices and environmental injustices, especially in resource-rich areas of Africa and Southeast Asia. Recycling helps address these problems by lowering the demand for newly mined materials, supporting ethical sourcing. Reduced mining activity also decreases exposure to hazardous byproducts like radioactive waste and heavy metals for workers and local communities, improving public health outcomes.

6. Challenges and Strategic Solutions

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Although recycling NdFeB magnets offers benefits, there are obstacles to scaling up the process. Collecting magnets scattered across numerous small electronic devices presents logistical difficulties, which call for strong e-waste management systems featuring incentivized return programs and centralized collection points. Technological hurdles, such as the high energy consumption of hydrometallurgical leaching, demand advancements in hybrid techniques like bioleaching and increased automation to improve efficiency. Policy measures, including extended producer responsibility (EPR) requirements and tax incentives for using recycled materials, are essential to overcoming institutional resistance and encouraging industry participation.

6.DIFFERENT METHOD OF RECYCLING NdFeB MAGNET

Recycling NdFeB (neodymium–iron–boron) magnets has become increasingly important due to the rising demand for rare earth elements (REEs) such as neodymium (Nd), dysprosium (Dy), and praseodymium (Pr), as well as the environmental and economic concerns associated with primary mining. Over time, a variety of recycling methods have been developed, each offering distinct advantages and limitations depending on the specific application, the kind of product being recycled at the end of its life, and the purity level needed for the recovered materials. In general, these techniques can be organized into five main categories

Mechanical Recycling (Physical Separation)

This technique involves physically dismantling and processing end-of-life products like mobile phones, hard drives, or electric motors to extract NdFeB magnets. Common mechanical processes include crushing, grinding, milling, and magnetic separation.

Advantages: It is cost-effective, environmentally friendly, and suitable for magnets that can be reused or reprocessed with minimal treatment.

Limitations: It does not enable recovery of individual elements, and contaminants may restrict its use in remanufacturing.

1. Hydrogen Decrepitation (HD)

Hydrogen decrepitation exposes NdFeB magnets to hydrogen gas, which penetrates their microstructure and causes embrittlement along grain boundaries. This leads to the magnet breaking down into a fine powder, making further processing easier.

Advantages: Magnetic properties are preserved; it serves as a pretreatment step for chemical extraction or re-sintering.

Limitations: Requires careful hydrogen handling and may be less effective for magnets that are oxidized or coated.[7]

2. Chemical Leaching

Chemical leaching selectively dissolves rare earth elements (REEs) from magnet materials using acidic solutions.

Inorganic Acid Leaching: Uses strong mineral acids such as hydrochloric acid (HCl), nitric acid (HNO_3), or sulfuric acid (H_2SO_4) to dissolve the magnet matrix.

Drawbacks: Generates hazardous waste, is highly corrosive, and raises environmental concerns.

Organic Acid Leaching: Uses environmentally friendly acids like lactic, citric, acetic, or oxalic acid.

Advantages: Lower environmental impact, better selectivity, and potential integration into green chemistry approaches. These leaching processes are typically followed by precipitation, solvent extraction, or ion exchange to isolate and purify the REEs. [16]

3. Electrochemical Methods

Electrochemical recycling employs electrolytic cells to selectively dissolve or deposit REEs from magnet materials. Techniques include electrowinning, electrodeposition, and electrochemical dissolution.

Advantages: Offers high selectivity and purity of recovered elements with precise process control.

Limitations: Energy-intensive and requires advanced infrastructure.[14]

4. Direct Reuse and Remanufacturing

This approach avoids fully breaking down magnets, allowing them to be reused directly or reprocessed into new magnets through methods like hot pressing, sintering, or spark plasma sintering.

Advantages: Maintains much of the original magnetic performance and reduces the need for chemical processing.

Limitations: Requires high-quality and consistent feedstock and is limited to compatible waste streams.

5. Emerging and Hybrid Techniques

Bioleaching: Uses microorganisms to extract REEs; still in development and limited by slow reaction rates.

Microwave- and Ultrasound-Assisted Leaching: These methods improve leaching speed and efficiency by applying energy inputs and are currently being explored for industrial-scale use.

Each recycling method has distinct advantages depending on the intended application and the condition of the discarded magnets. Often, a combined approach—such as pairing hydrogen decrepitation with organic acid leaching—is employed to maximize recovery efficiency while minimizing environmental impact. Ongoing research focuses on optimizing these processes to promote sustainable recovery of rare earth elements and support the development of a circular economy for magnet materials.[15]

7.WHY LEACHING IS PREFERRED FOR RECYCLING NdFeB MAGNETS ?

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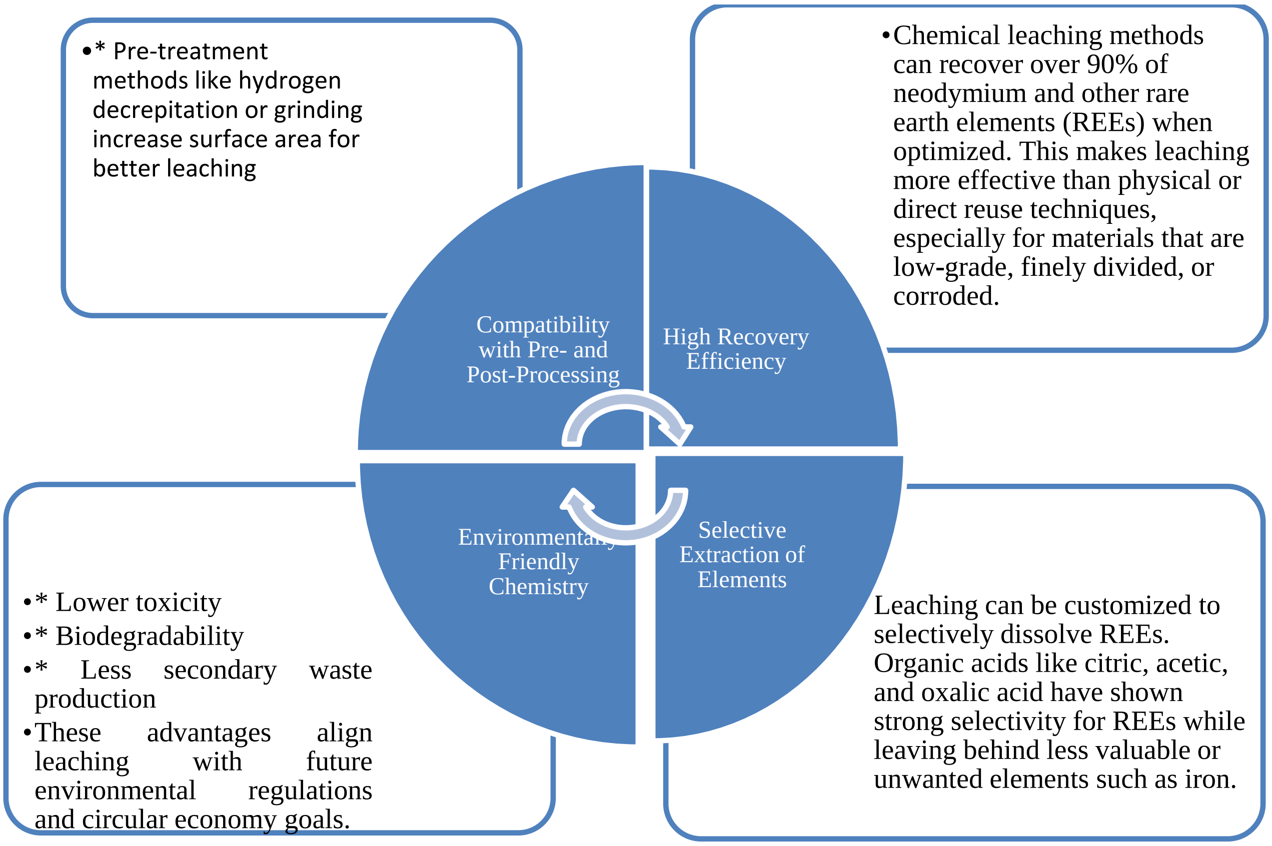
Recycling of NdFeB (neodymium–iron–boron) magnets has gained increasing attention due to their high rare earth element (REE) content, critical supply risk, and importance in modern green technologies. Among various recycling strategies, chemical leaching has emerged as a preferred method for recovering REEs such as neodymium (Nd), dysprosium (Dy), and praseodymium (Pr) from end-of-life magnets.

7.1 BENEFITS OF LEACHING IN RECYCLING NdFeB MAGNETS



- * Pre-treatment methods like hydrogen decrepitation or grinding increase surface area for better leaching

- Chemical leaching methods can recover over 90% of neodymium and other rare earth elements (REEs) when optimized. This makes leaching more effective than physical or direct reuse techniques, especially for materials that are low-grade, finely divided, or corroded.

- * Lower toxicity
- * Biodegradability
- * Less secondary waste production
- These advantages align leaching with future environmental regulations and circular economy goals.

Leaching can be customized to selectively dissolve REEs. Organic acids like citric, acetic, and oxalic acid have shown strong selectivity for REEs while leaving behind less valuable or unwanted elements such as iron.

- Post-treatment techniques such as solvent extraction, ion exchange, or precipitation help purify the recovered REEs

Method	Ree Recovery	Purity	Environmental Impact	Scalbility	Process Complexity
Mechanical Separation	Low	Low	Low	High	Low
Hydrogen Decrepitation	Medium	Medium	Medium	Medium	Medium
Leaching (Inorganic)	High	High	High(Toxic)	High	Medium
Leaching (Organic)	High	High	Low(Eco-Friendly)	Medium High	Medium
Electrochemical Recovery	High	Very High	Medium	Medium	High
Direct Reuse/Remanufacture	Medium	Medium	Low	Low	Medium

Table 1

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8.DEEP EUTECTIC SOLVENTS

Deep eutectic solvents (DESs) are increasingly recognized as a new category of ionic liquid (IL) analogues because they share many features and properties with ILs. Although the terms DES and IL are often used interchangeably in the literature, it is important to clarify that they are actually two distinct types of solvents. DESs are created from a eutectic mixture of Lewis or Brønsted acids and bases, which can include various anionic and/or cationic species. In contrast, ILs consist mainly of one specific type of discrete anion and cation. This highlights that while DESs have physical properties similar to other ILs, their chemical characteristics indicate they are suited for quite different applications.[13]

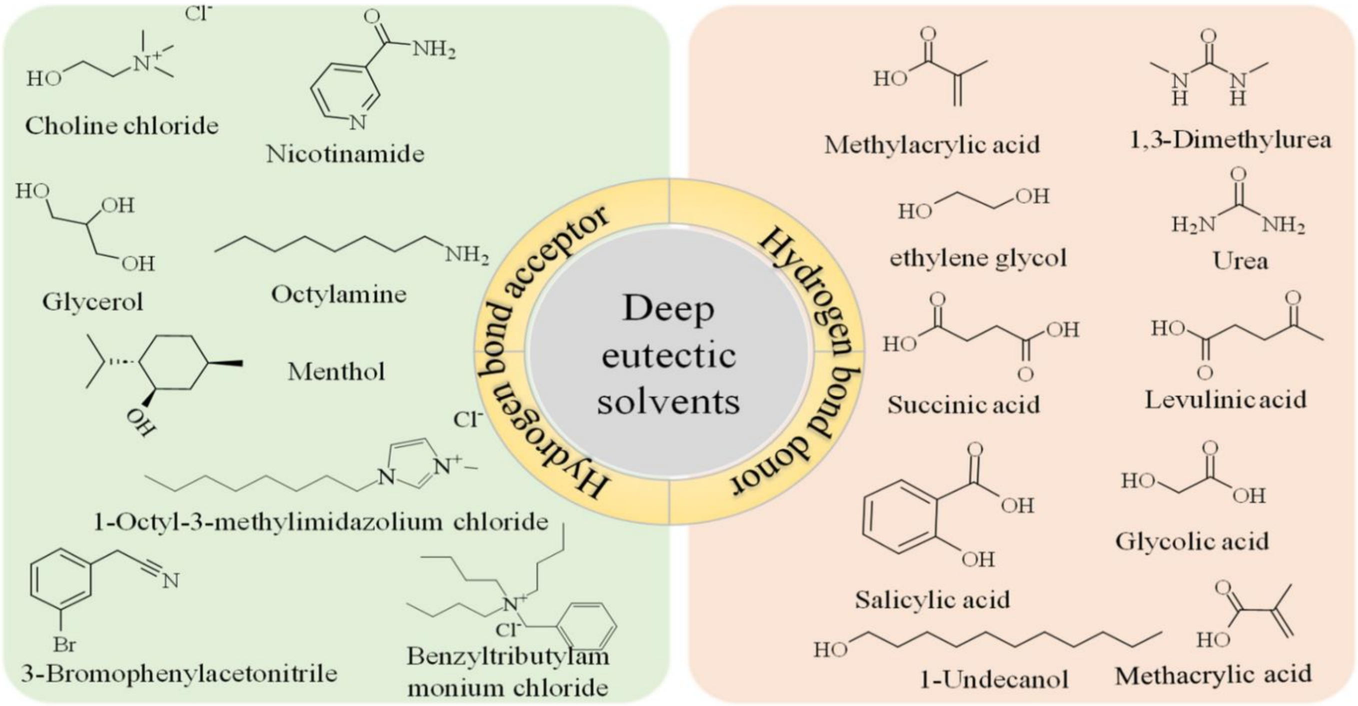
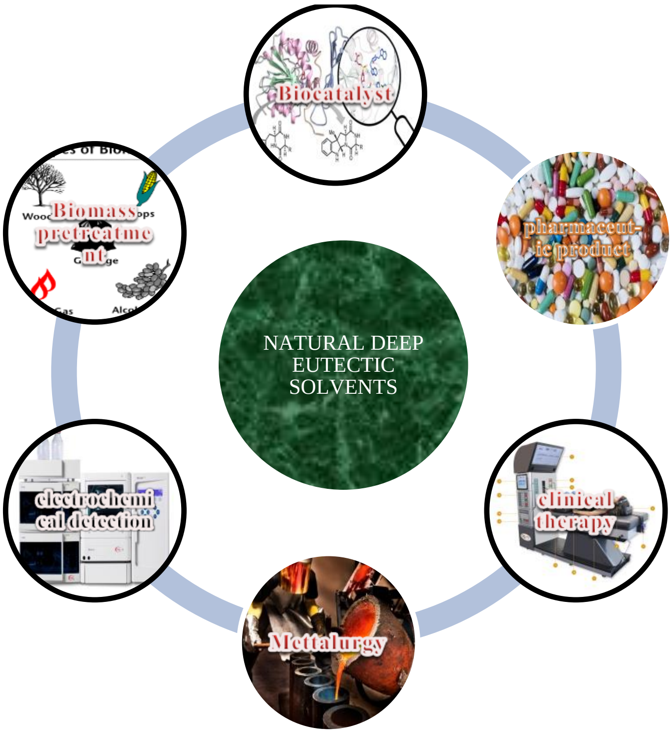


Figure 4

8.1USE OF DEEP EUTECTIC SOLVENTS



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8.2WHY DEEP EUTECTIC SOLVENT IS USED OVER CONVENTIONAL SOLVENT ?

The growing need for rare earth elements (REEs) like neodymium (Nd), dysprosium (Dy), and praseodymium (Pr), especially for manufacturing NdFeB magnets utilized in advanced technologies, has driven the development of sustainable and effective recycling techniques. In this context, the use of Deep Eutectic Solvents (DESs) has appeared as a promising substitute for conventional mineral acid-based leaching methods.

1. Environmental Sustainability and Adherence to Green Chemistry Principles

Deep eutectic solvents (DESs) are generally made up of a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA), forming a eutectic mixture with a melting point much lower than that of the individual components. These solvents often contain biodegradable and non-toxic substances, such as choline chloride and organic acids like oxalic acid or lactic acid, making them environmentally friendly and aligned with green chemistry guidelines. In contrast, traditional solvents—mainly strong mineral acids like hydrochloric acid (HCl), nitric acid (HNO_3), and sulfuric acid (H_2SO_4)—are highly corrosive, generate toxic waste, and pose health risks, requiring expensive waste management and environmental protection measures. [11]

2. Enhanced Selectivity for Extracting Rare Earth Elements

DESs show a high level of selectivity for rare earth elements (REEs) compared to transition metals such as iron (Fe), cobalt (Co), and nickel (Ni), which are also found in NdFeB magnets. This selectivity can be adjusted by modifying the combination of the HBA and HBD, enabling targeted dissolution of specific elements. For instance, DESs made from choline chloride and oxalic acid have demonstrated strong binding with trivalent REE ions, facilitating efficient separation from other matrix elements and easing subsequent purification steps.

3. Low Volatility and Improved Process Safety

One major benefit of DESs compared to traditional solvents is their almost zero vapor pressure, which greatly lowers the risks associated with solvent evaporation, flammability, and the release of toxic gases. This characteristic improves the safety of the recycling operation and reduces solvent loss during processing. Additionally, DESs are thermally stable and can operate effectively over a broad temperature range, further enhancing the reliability of the process.

4. Reusability and Process Integration

Unlike mineral acids that typically need to be neutralized and discarded after one use, DESs can be recovered and reused multiple times with little degradation, depending on impurity levels. This ability to recycle DESs significantly cuts down on overall costs and environmental impact. Moreover, DES-based systems can often combine leaching and precipitation steps into a single stage—particularly when using oxalate-containing DESs—allowing for the direct formation of rare earth element (REE) oxalates on-site.

5. Energy Efficiency and Scalability

Many DES formulations work well under mild conditions (from room temperature up to 80 °C), which lowers the energy required compared to high-temperature acid leaching. This not only boosts the energy efficiency of the process but also makes it more suitable for decentralized or small-scale recycling setups. Furthermore, DESs have demonstrated compatibility with process intensification methods like ultrasound and microwave-assisted leaching, which can speed up metal recovery rates and improve overall process throughput.

Property	**Deep eutectic solvents**	**Conventional mineral acid**
Environmental impact	Low(bio degradable non toxic)	High(hazardous)
Selectivity of REE	High(tunablecomplexation)	Moderate(non selective)
Volatility and handling safety	Very low (non volatile)	High(volatile)
Reusability	High	Low(single use typically)
Metal co-extraction	Low	High(fe,co and other co-dissolve)
Energy recuirements	Low to moderate	Moderate to high
Scalability potential	Medium to high	High(with waste treatment nee

9.MATERIALS AND METHODS

9.1 MATERIALS

Commercially available neodymium–iron–boron (NdFeB) magnet scraps were used as the source of neodymium (Nd). The magnets were manually demagnetized by heating in a muffle furnace at 600 °C for 2 hours. The demagnetized magnets were then

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ground and sieved to obtain particles smaller than 150 µm. Glycine ($C_2H_5NO_2$, ≥99%) and lactic acid ($C_3H_6O_3$, ≥85 The following variables were used in the :

- **Organic acids: acetic acid (CH_3COOH) ,citric acid ($C_6H_8O_7$),Malonic acid ($C_3H_4O_4$),Lactic acid ($C_3H_6O_3$)**
- **Acid concentrations: 1M, 3M, 5M mol/L;**
- **Solid-to-liquid ratios: 1/40, 1/30, and 1/20 (g/mL);**
- **Leaching time: 1hour,2hour,3hour,4 hour**

Leaching Efficiency Calculation

Leaching efficiency was calculated using the following equation:

$$E\ (\%) = \left(\frac{w_{l,i}}{w_{i,i}}\right) \times 100$$

Where

E=leaching efficiency %

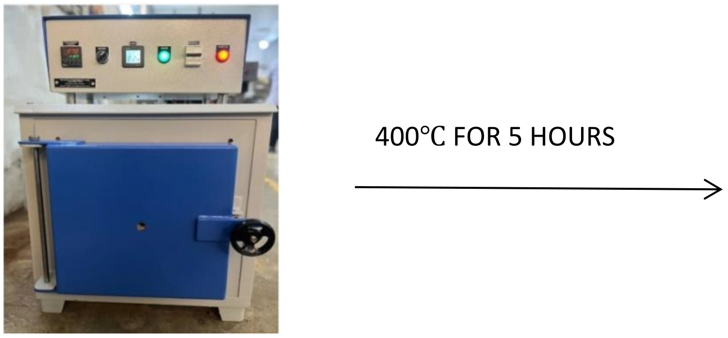
$w_{l,i}$ is the amount of rare earth element i in the leachate (mg/kg),

$w_{i,i}$ is the total amount of rare earth element i in the digested sample (mg/kg).

9.2 METHOD

The thermal demagnetization of NdFeB magnets recovered from hard disks requires heating them to a temperature above their specific Curie point. Mobile phone magnets typically have a Curie temperature of about 312°C, but hard disk magnets can differ depending on their composition—certain additives, such as Dy or Co, can raise the Curie temperature. In this study, differential thermal analysis confirmed that the hard disk magnets had a Curie temperature of approximately 450°C. The samples were then held at 450°C for 120 minutes to ensure complete disruption of domain alignment. During this process, a mass loss of around 2.80% was recorded, which is slightly lower than for mobile phone magnets. This difference is likely because hard disk magnets are protected by a nickel coating that helps reduce surface oxidation. The coating may also partially slow volatilization, although some oxidized surface layers still detached.

For the grinding step, hard disk magnets—often larger and enclosed in metal housings were first decapsulated using pliers to remove their protective shells. Manual grinding with a mortar and pestle was found to remain the most effective method, since mechanical approaches (such as knife mills) still resulted in roughly 15% material loss. This was attributed to the magnets' irregular shapes and residual metallic fragments sticking to the equipment. When grinding was done manually, loss was limited to about 5%, providing a good balance between efficiency and yield. Pre-crushing with hydraulic shears was also tested, but it was discontinued due to safety concerns caused by flying shards. The final powder was sieved to <500 µm and was suitable for subsequence leaching



9.2.1DES PREPARATION

A natural deep eutectic solvent (NADES) was prepared from lactic acid and glycine at a molar ratio of 7:1. Briefly, 78.8 mL of lactic acid and 11.26 g of glycine were measured accurately and introduced into a clean, dry beaker. The components were stirred continuously with a magnetic stirrer at room

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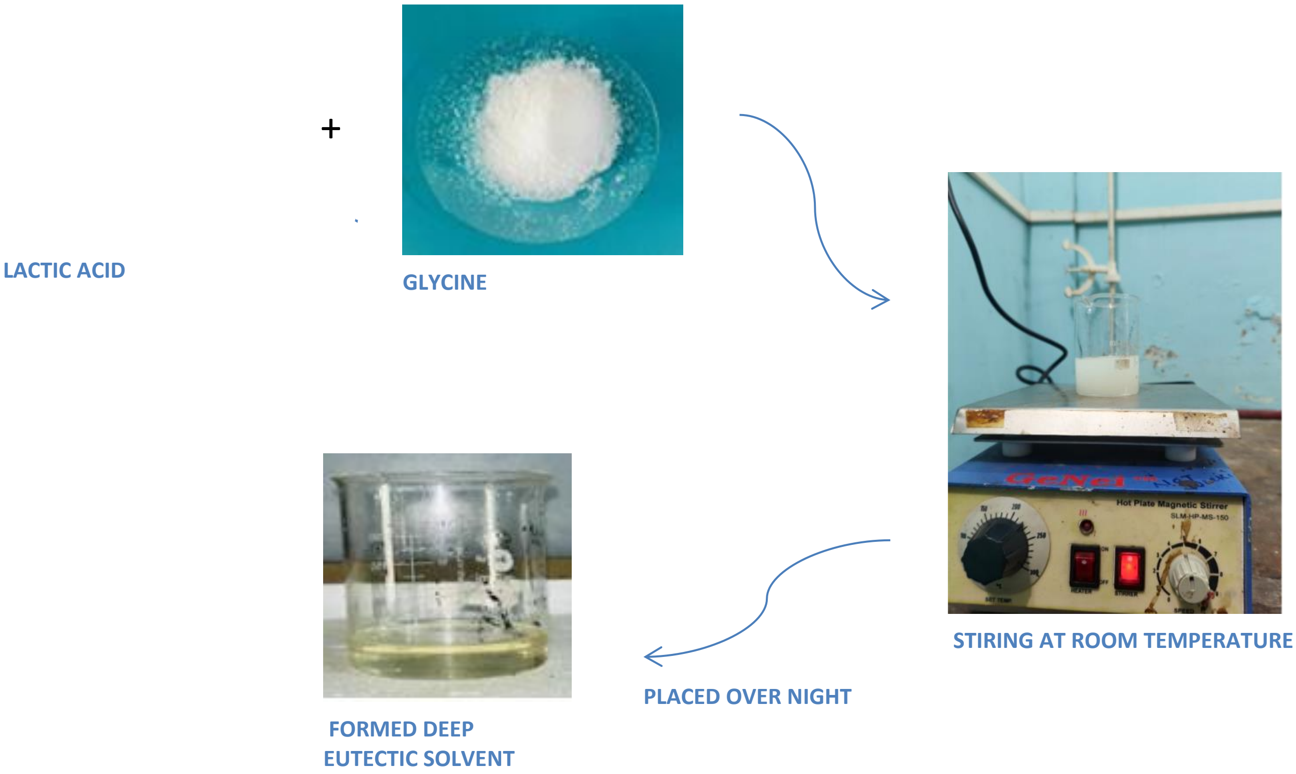
temperature for 1 h and 10 min. Mixing was maintained until a homogeneous, transparent solution appeared, which confirmed the successful formation of the NADES. No external heating was applied throughout the preparation. Afterward, the obtained solution was covered and left undisturbed overnight at room temperature to ensure stability and to minimize any potential contamination.



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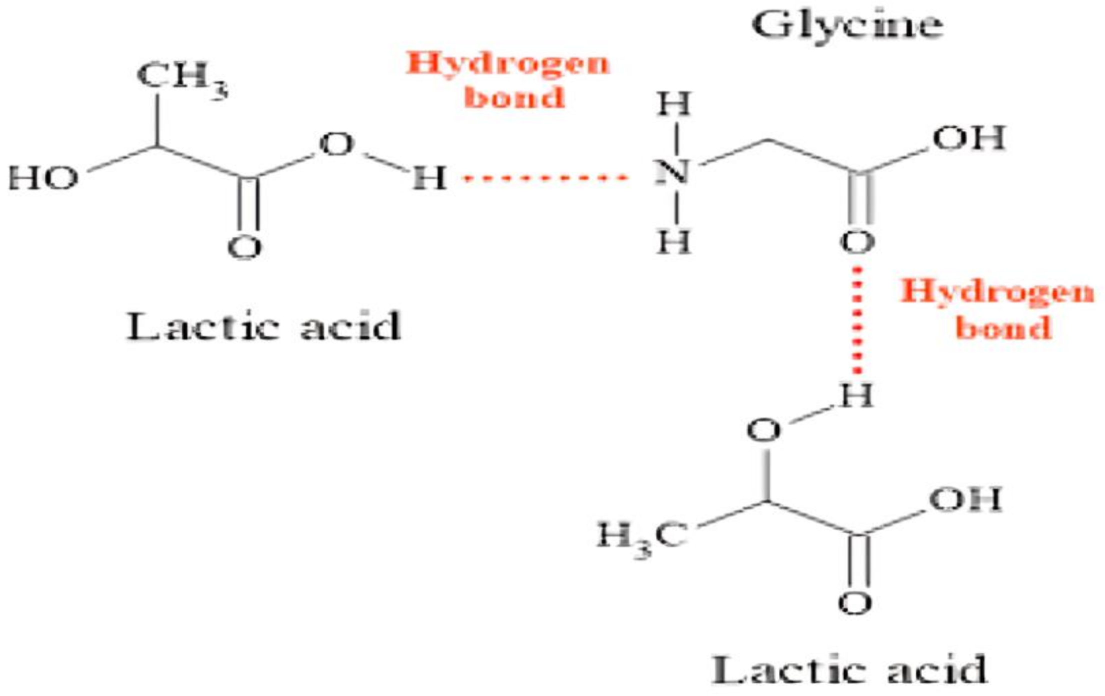
There may be the possible interaction between lactic acid & glycine through the hydrogen bonding between the hydrogen of lactic acid & nitrogen of glycine.



9.2.2 LEACHING PROCEDURE.

Initially, all the apparatus were rinsed with acetone to remove any impurities. After that, the leaching experiments were conducted by introducing 1.0 g of finely ground NdFeB magnet powder into (20–40) mL of the prepared NADES placed in a 100 mL beaker. The resulting mixture was stirred at 300 rpm, while the leaching was carried out at various temperatures ranging from 25 to 60 °C. At predetermined time intervals (1–4 h), samples were taken, filtered, and then analyzed in order to measure the neodymium concentration.[10]

Leaching with Lactic acid :-

To assess how contact time affects neodymium recovery, leaching experiments were conducted using a leaching agent made from a mixture of lactic acid and glycine. In each experiment, 1.0 g of ground NdFeB magnet powder (particle size <150 µm) was combined with 20 mL of an aqueous lactic acid solution in a 100 mL glass beaker. The slurry was stirred continuously at 300 rpm with a magnetic stirrer to promote uniform dispersion and effective contact between the solid and liquid phases.

All experiments were carried out at a constant temperature of 50°C (as specified elsewhere in the study), while the leaching time was varied from 1 to 4 hours. At set time intervals (for example, 1, 2, 3, and 4 hours), samples were withdrawn to track how neodymium dissolution changed over time. Each sample was immediately filtered to remove any undissolved residues. The filtrate obtained was then collected and stored for subsequent analysis. The concentration of neodymium in the leachate was later measured to evaluate the leaching efficiency at each time point.

. 10.PHYSICOCHEMICAL PROPERTIES TESTS:

Fourier-Transform Infrared Spectrometry (FTIR):

PerkinElmer Inc., Shelton, CT, USA, employed the Fourier-transform infrared spectrometer Spectrum 3 (FTIR, L1280127) to analyze the molecular interactions between the NADESs' constituent parts. At room temperature, the spectra of NADES samples (0.05 mL aliquots) were captured at a wavelength between 4000 and 400 cm−1.

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DENSITY MEASUREMENTS

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VISCOSITY:

The viscosity studies of the NADES were performed using a Ostwald’s viscometer. In triplicate, the viscometer was calibrated using ultrapure water at 25 °C. The system's temperature was managed by an external thermostatic water bath.

SURFACE TENSION:

A Stalagmometer was used to measure the surface tension of all the investigated NADESs at different temperatures

IONIC CONDUCTIVITY:

The ionic conductivity of the NADES was measured by conductivity meter.

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11.ANALYSIS

This study examined the physicochemical properties of NADESs formulated with lactic acid. Because lactic acid is a liquid, it produces clear fluids at low temperatures through fast reactions with other NADES components. Our results, along with published data, indicate that solvent physicochemical properties change when NADESs are modified with water. However, once more than 50% water was added, the intermolecular interactions responsible for forming the eutectic network disappeared, leading to a simple aqueous solution of the NADES components. Therefore, across different concentrations, we investigated both native NADESs and NADES solvents diluted with water.

Physicochemical Properties:

1. FTIR

The formation of the deep eutectic solvent (DES) composed of glycine and lactic acid was confirmed through comparative FTIR spectral analysis of the individual components and their mixed system. The spectrum of the DES exhibits a pronounced broadening and red shift in the 3200–3600 cm^{-1} region relative to pure glycine and lactic acid, corresponding to overlapping O–H and N–H stretching vibrations. This broadening is indicative of the establishment of an extensive hydrogen-bonding network between the hydroxyl groups of lactic acid (hydrogen bond donor) and the amine/carboxylate functionalities of glycine (hydrogen bond acceptor). Furthermore, the characteristic C=O stretching vibration of lactic acid, typically observed around ~1700 cm^{-1}, is shifted to lower wavenumber and appears less defined in the DES spectrum, suggesting a weakening of the carbonyl bond due to its participation in intermolecular hydrogen bonding. Additional modifications are evident in the fingerprint region (1500–1000 cm^{-1}), where peak shifts, intensity variations, and partial merging of bands are observed, reflecting changes in C–O and C–N vibrational environments arising from supramolecular interactions. Notably, the DES spectrum does not represent a simple superposition of the spectra of the individual, thereby confirming the formation of a new, structurally distinct hydrogen-bonded liquid phase. Collectively, these spectral features provide strong evidence for the successful formation of a glycine–lactic acid deep eutectic solvent mediated by specific and cooperative intermolecular hydrogen bonding interactions..[8]

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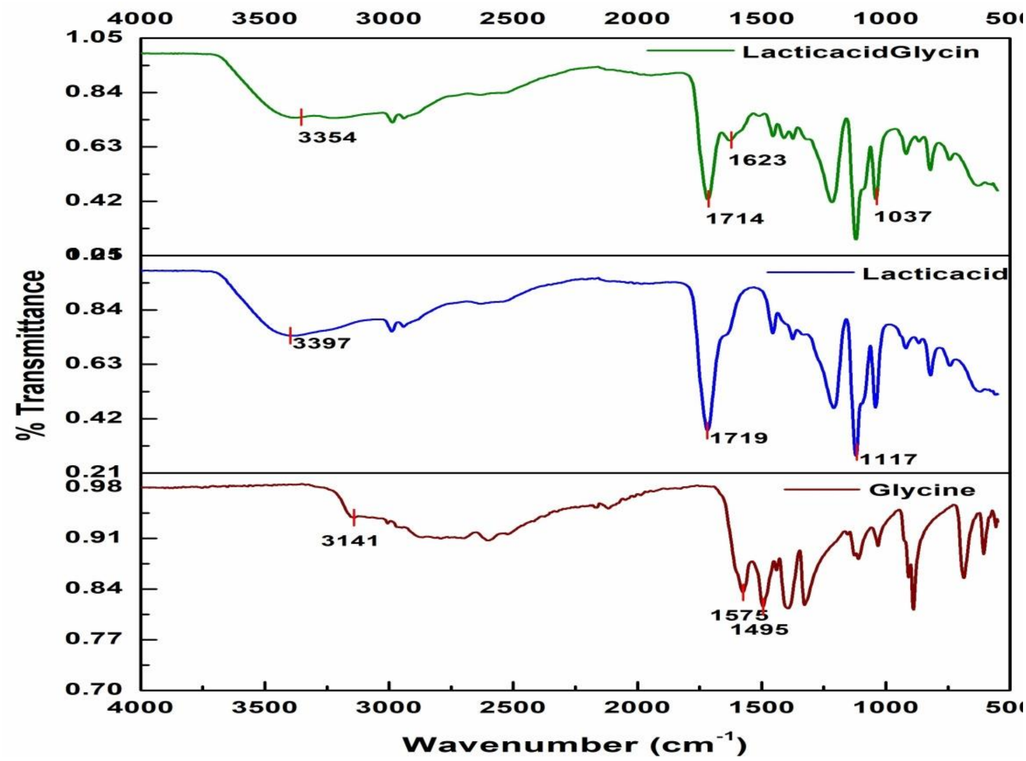
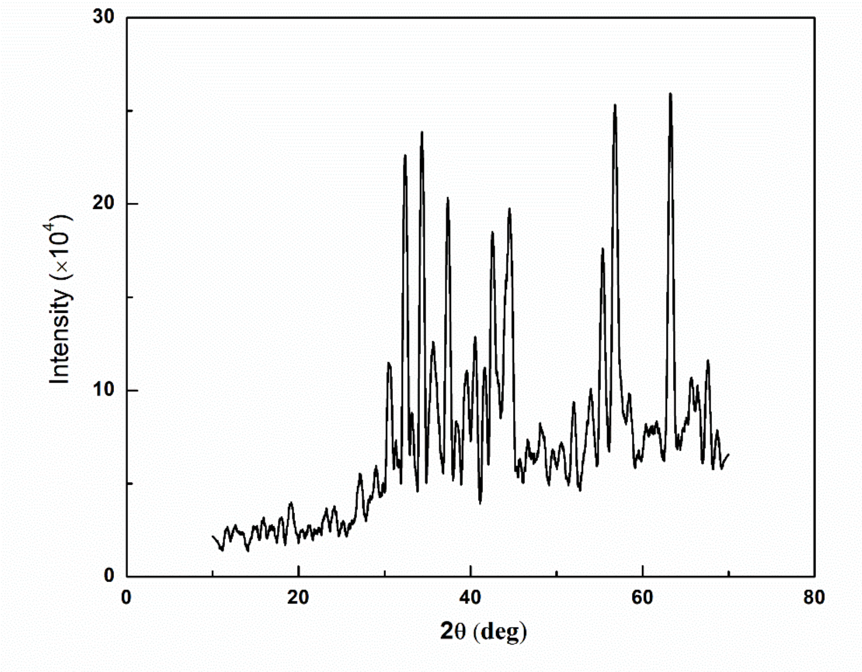


2. XRD ANALYSIS

the presence of sharp and distinct peaks represent the crystalline nature.



AGITATION AND TIME

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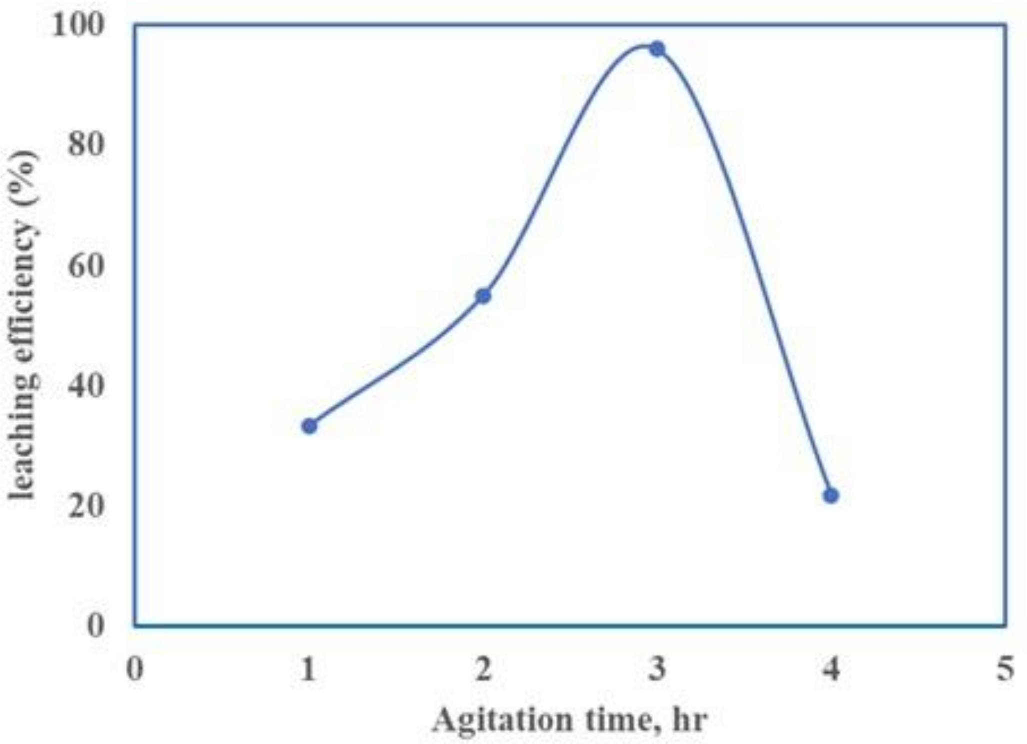
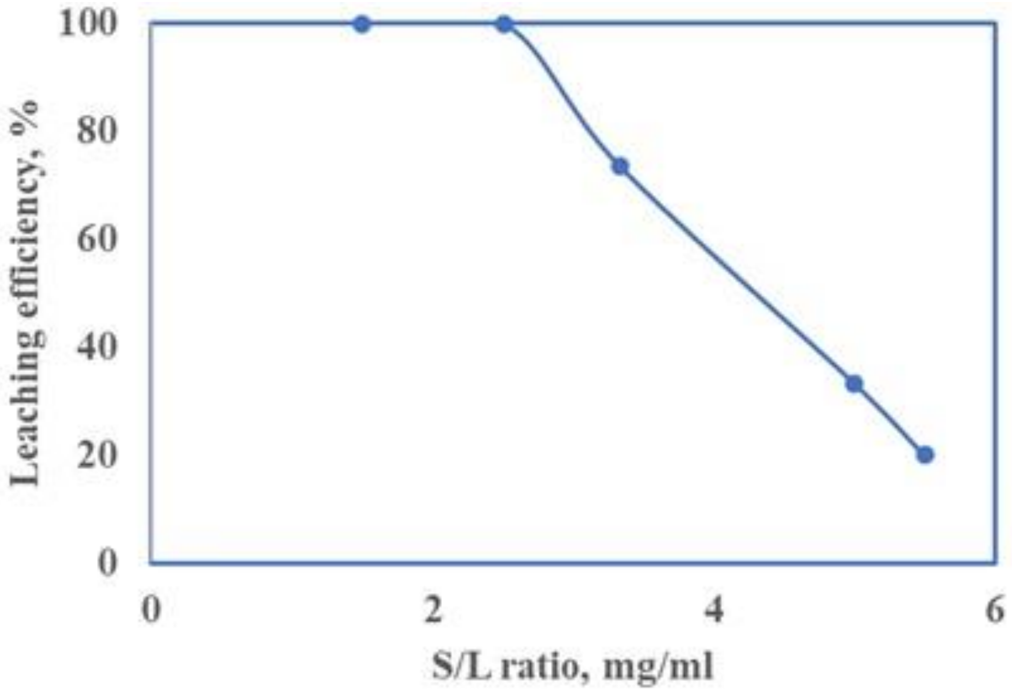


Leaching efficiency increase with increase in agitation time upto 3 hour and decreases after that

LEACHING EFFICIENCY WITH VARIOUS SOLID LIQUID RATIO

Leaching efficiency increase with increase in S/L ratio



VARIATION WITH TEMPERATURE

Leaching efficiency increase with increase in temperature and give highest efficiency at 60℃

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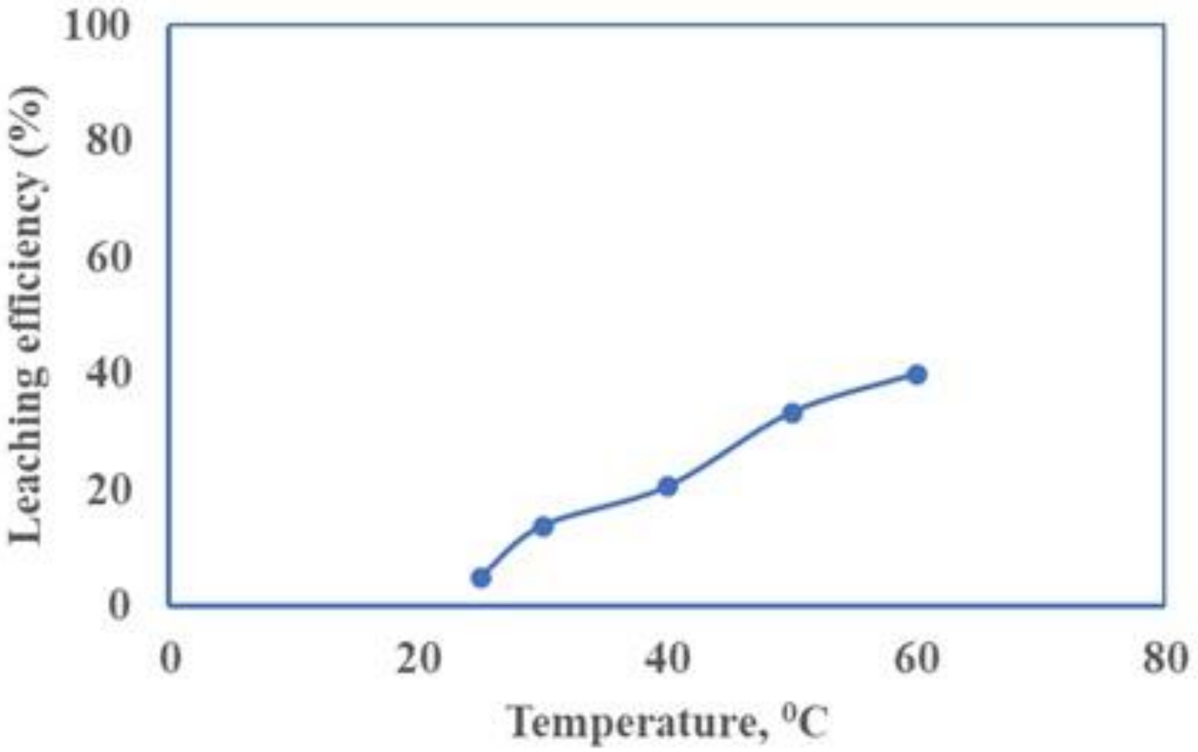

12.RESULT AND DISCUSSION

In this work, neodymium (Nd) was recovered from NdFeB magnets using a Natural Deep Eutectic Solvent (NADES) formed by glycine and lactic acid. These magnets are commonly used in electronic products, including hard drives, and they can serve as a valuable secondary supply of rare earth elements. Using NADES also fits well with green chemistry principles, since the solvent is made from natural, biodegradable, and low-toxicity constituents.

The leaching conditions were improved by adjusting three main variables: temperature, leaching time, and the solid-to-liquid (S/L) ratio. The highest Nd recovery efficiency, 73%, was achieved under the conditions of 50 °C, a leaching time of 3 hours, and an S/L ratio of 1:20. When the temperature was increased to above 90 °C, the efficiency declined, most likely because the NADES underwent thermal decomposition. Because an intact and stable solvent is important for leaching metals effectively, such decomposition at higher temperatures would reasonably be expected to weaken the recovery performance.

Shorter leaching times (below 0.5 hours) were also found to be inadequate for complete Nd extraction. This result suggests that the solvent requires enough time to interact effectively with the magnet material. The behavior can be explained by the kinetics of the leaching reaction, as longer contact times generally favor metal dissolution.

A particularly notable result was the synergistic effect of the glycine–lactic acid combination. Glycine contains an amino group that can act as a ligand to bind metal ions, while lactic acid provides the acidic medium needed to dissolve metal oxides. Taken together, the two components appear to generate more effective complexes than when each is used alone.

For comparison, further experiments were performed with other organic acids, including citric acid, malonic acid, and acetic acid. Nd recovery was evaluated by UV-Vis spectroscopy, and 660 nm was identified as the wavelength with the strongest response, displaying the largest absorbance peak in the visible region. Accordingly, 660 nm was selected to follow Nd concentration throughout the leaching process.

CONCLUSION

The study confirms that the leaching efficiency of rare earth recovery is strongly dependent on operating parameters. Efficiency increases with higher temperatures and longer agitation times, while it decreases with an increase in the solid-to-liquid ratio. The optimum recovery was achieved at 60 °C with an agitation time of 3 hours, underscoring the role of thermal activation and sufficient contact duration in enhancing leaching kinetics. In this work, Nd was successfully recovered from NdFeB magnets, whose composition primarily includes boron, iron, neodymium, and praseodymium. These results highlight that careful control of process variables can maximize recovery yields, while also demonstrating the feasibility of extracting valuable rare earth elements

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from secondary sources such as permanent magnets. Overall, the findings provide a pathway toward sustainable and efficient rare earth extraction, contributing to resource recovery and circular economy initiatives.

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