Physicochem. Probl. Miner. Process., 62(3), 2026, 224969

http://www.journalssystem.com/ppmp

Physicochemical Problems of Mineral Processing

ISSN 1643-1049

Deep eutectic solvents for sustainable recovery of critical and rare metals from primary and secondary resources: A review

Mert Sarıkaya [1], Fatma Elif Genceli Güner [2], Birgül Benli [1]

[1] Department of Mineral Processing Engineering, Istanbul Technical University, 34469, Istanbul, Türkiye

[2] Department of Chemical Engineering, Istanbul Technical University, 34469, Istanbul, Türkiye

Corresponding author: benli@itu.edu.tr (Birgül Benli), sarikayam19@itu.edu.tr (Mert Sarıkaya)

Abstract: The growing demand for critical raw materials and increasing environmental concerns have intensified interest in sustainable metal recovery from both primary ores and secondary resources. While conventional extraction from ores remains essential, it is often associated with high energy consumption, reagent use, and environmental impacts. In parallel, recovery from secondary sources such as electronic waste (e-waste), industrial by-products, and end-of-life products has emerged as a key strategy within urban mining and circular resource utilization. Deep eutectic solvents (DESs) have recently gained attention as tunable solvent systems due to their adjustable physicochemical properties, relatively simple preparation, and potential environmental advantages. DES-related research has increased significantly, with a notable rise in DES-based leaching studies since 2018. This review provides a comprehensive overview of DES applications in the recovery of critical and rare metals from both primary ores and secondary resources, emphasizing physicochemical properties, selective leaching behavior, operating conditions, process flowsheet considerations, and downstream recovery challenges. DESs have been applied in spent lithium-ion batteries, permanent magnets, primary ores, waste printed circuit boards (WPCBs), coal fly ash, metallurgical slags, and red mud. These studies highlight the potential of DESs for processing complex matrices and enabling selectively dissolution of target metals under specific solvent and process conditions. By integrating this review critically evaluates the scientific and practical significance of DESs in improving metal selectivity, reducing reliance on aggressive mineral acids, and supporting circular economy strategies, while identifying key challenges related to solvent stability, recyclability, downstream recovery, process integration, and scale-up.

Keywords: deep eutectic solvents (DESs), selective leaching, critical metals, secondary resources, mineral processing

1. Introduction

In the era of sustainable development and heightened awareness of resource scarcity, the mining and mineral processing industries confront significant challenges (Pavloudakis et al., 2024). These challenges encompass not only the environmental impact and energy consumption but also the economic feasibility of extracting metals from lower-grade ores (An et al., 2023). One promising strategy to tackle these issues is the adoption of green solvents, with Deep Eutectic Solvent (DES) standing out prominently (Kaplan et al., 2025; Li et al., 2025; Svärd et al., 2024; Hansen et al., 2020; Paiva et al., 2014). These green solvents are designed to be environmentally friendly exhibiting low toxicity, high biodegradability, and minimal ecological footprint, making them suitable for sustainable industrial applications. Among them, deep eutectic solvents (DESs) have garnered considerable attention due to their unique and tunable physicochemical properties. Although DESs share several characteristics with ionic liquids (ILs), such as low volatility, strong solvation ability and adjustable solvent properties, they should not be considered simply as a subclass of ILs. ILs are generally composed entirely of discrete ions, whereas DESs are typically formed by combining hydrogen bond acceptors (HBA) and hydrogen bond donors (HBD), resulting in eutectic mixtures with melting point significantly lower than those of

DOI: 10.37190/ppmp/224969

the individual components. Compared with many conventional ILs, DESs are often easier to prepare, less expensive, and may offer advantages in terms of biodegradability and environmental compatibility; however, these properties strongly depend on their specific composition. Therefore, DESs can be regarded as IL- like solvent systems that provide a promising alternative to conventional solvents in mineral processing and metal recovery applications, particularly in metal leaching, solvent extraction, and selective recovery processes (Smith et al., 2014; Hansen et al., 2020; Jenkin et al., 2016; Khan et al., 2026).

Integrating DES into mineral processing operations can significantly enhance this approach. By reducing reliance on hazardous chemicals, lowering energy consumption, and mitigating the environmental footprint associated with mining activities, DESs enable more efficient and environmentally friendly extraction processes. This approach not only aligns with sustainable development goals but also opens new opportunities for improving the efficiency and sustainability of mineral resource utilization. Furthermore, due to their non-toxic nature, biodegradability, and especially their reusability, DESs are emerging as cost-effective and advantageous alternatives (Liu et al., 2020).

Fig. 1 illustrates the relationship between the potential use of DESs and key areas of urban mining. In this context, the recovery of precious metals from secondary sources such as electronic waste (e-waste), industrial by-products, and end-of-life products emerges as a crucial strategy. This approach mitigates the environmental hazards associated with traditional mining and promotes a more sustainable and circular approach to resource management. The figure highlights the principles of sustainable mining operations and their influence on essential domains. Sustainable mining aims to minimize environmental impact, ensure economic viability, and uphold social responsibility. Recovering precious metals from these secondary sources is not just an environmental imperative but also a strategic response to resource scarcity. It promotes a circular economy where waste is transformed into resources, thereby reducing the environmental footprint of mining, lowering energy consumption, and diminishing the need for new mining projects.

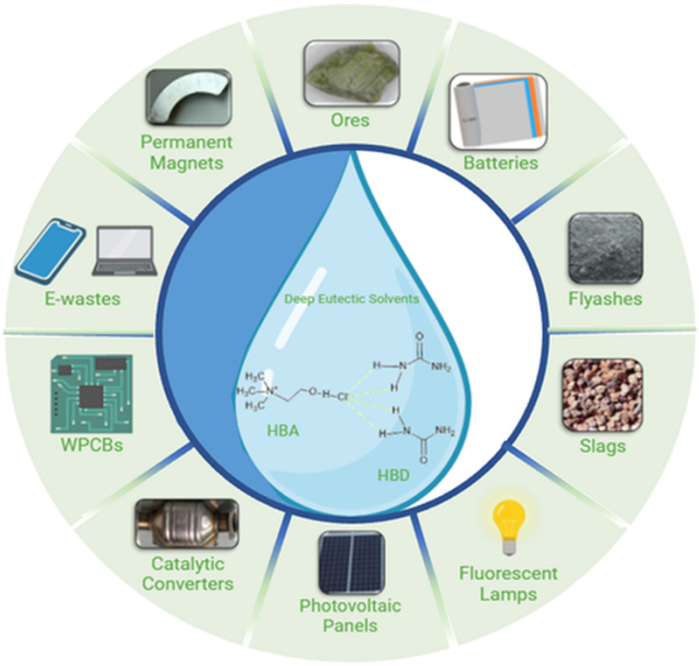

Fig. 1. Application of sustainable mining practices by integrating DES and recycling of primary and secondary resources

DES-based metal recovery processes can also be linked to several Sustainable Development Goals (SDGs), particularly SDG 6, SDG 9, SDG 12, and SDG 13, which emphasize clean water and sanitation, sustainable industrial innovation, responsible consumption and production, and climate action, respectively (United Nations, 2015). By enabling the recovery of valuable metals from secondary

resources such as e-waste, spent batteries, permanent magnets, slags, and fly ash, DESs can contribute to SDG 12, responsible consumption and production, through improved resource efficiency and circular material use. Their potential to reduce the use of aggressive mineral acids and hazardous reagents is also relevant to SDG 6, clean water and sanitation, by minimizing the generation of contaminated acidic effluents. In addition, DES-based processes may support SDG 9, industry, innovation and infrastructure, by promoting the development of innovative and more sustainable hydrometallurgical technologies. When integrated with low-energy and recyclable process designs, DESs may further contribute to SDG 13, climate action, by reducing the environmental footprint and energy intensity of metal recovery operations. However, these contributions depend strongly on solvent stability, recyclability, toxicity, downstream recovery, and life-cycle performance.

Recent data obtained from the Web of Science Core Collection database demonstrate a remarkable increase in publications related to deep eutectic solvents over the last fifteen years. The publication trend shown in Fig. 2 was obtained using the topic search term "deep eutectic solvent*" for DES-related publications and the combined search terms "deep eutectic solvent*" AND "leaching" for DES-based leaching studies. The search was conducted in 2025, the timespan was limited to 2010–2025, and the results were filtered by publication year to obtain the annual number of records. This analysis was used only to illustrate the general publication trend and was not intended as a comprehensive bibliometric analysis. As shown in Fig. 2, the total number of DES-related publications increased from only a limited number in 2010 to more than 3000 publications in 2025, indicating the rapid expansion of DES research across chemistry, materials science, environmental engineering, and separation technologies. A similar but more recent trend is observed for DES-based leaching studies, which remained relatively limited before 2018 but increased sharply thereafter, reaching more than 160 publications in 2025. This trend indicates that DES-based leaching has emerged as a rapidly growing subfield within DES research, particularly in relation to sustainable metal recovery, urban mining, and critical raw material processing.

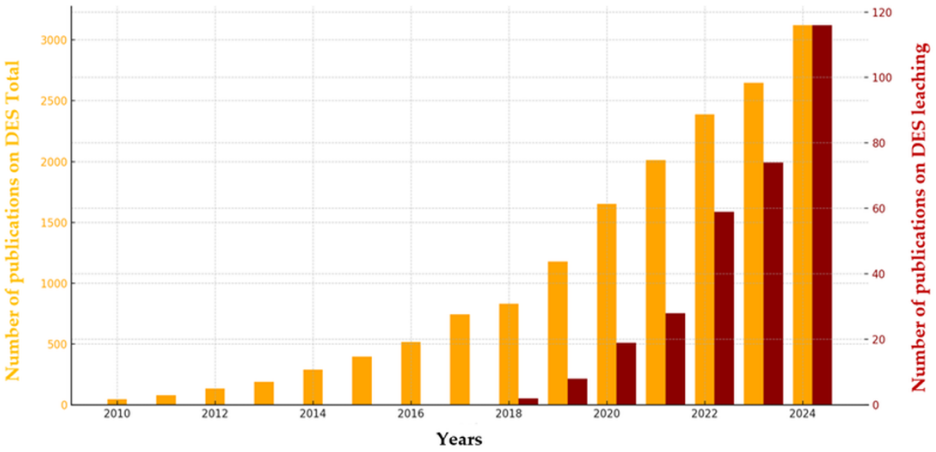

Fig. 2. Yearly growth of scientific publications on deep eutectic solvents and and DES-based leaching studies between 2010 and 2025 based on Web of Science Core Collection records.

Each of these areas plays a vital role in the successful implementation of sustainable mining practices, by balancing economic growth with ecological preservation and social responsibility. Although DESs have attracted considerable attention in academic research and in several chemical and materials-related processes, their implementation in metallurgical applications remains largely at laboratory or pre-industrial scale. Therefore, the incorporation of DES-based green chemistry approaches into the recovery and processing primary and secondary resources should be considered a promising but still developing strategy to address resource scarcity. Further advances in solvent stability, recyclability, downstream metal recovery, process integration, and environmental assessment are required before DES-based processes can be broadly implemented in sustainable mineral processing.

Recent patent activity, including EP3596241B1 on rare earth element recovery, US20200399737A1 on Li-ion battery recycling using green solvents, and CN117940592A on hydrophobic DES-based leaching

systems, further indicates growing technological interest in the commercialization potential of DES-based metal recovery processes. However, broader implementation still requires further advances in solvent stability, recyclability, downstream metal recovery, process integration, and scale-up validation. Although several review articles have discussed DESs in the broader context of green solvents, metal extraction, or specific secondary resources, many of them focus mainly on a single material group, such as spent lithium-ion batteries, electronic waste, rare earth magnets, or general solvent properties. In contrast, the present review provides an integrated mineral processing perspective by covering both primary ores and secondary resources within the same framework. Its unique contribution is the comparative evaluation of DES-based leaching across different metal-bearing matrices, including spent lithium-ion batteries, permanent magnets, primary ores, waste printed circuit boards, coal fly ash, metallurgical slags, and other industrial residues. In addition to summarizing recent leaching efficiencies, this review emphasizes physicochemical properties, selectivity mechanisms, operating conditions, process flowsheet considerations, solvent stability, recyclability, downstream metal recovery, and industrial implementation challenges. Therefore, the review aims not only to summarize recent advances, but also to critically identify the opportunities and limitations that must be addressed for the practical application of DESs in sustainable mineral processing and critical metal recovery.

2. Definition and classification of deep eutectic solvents (DESs)

DESs have emerged as a notable class of green solvents, although they were only formally recognized relatively recently, approximately two decades ago (Achkar et al., 2019), with the term first introduced by Abbott et al. (2003). However, the definition of DESs remains somewhat controversial, as the proposed definitions often fail to clearly distinguish them from other mixtures. In fact, mixtures of solid compounds typically exhibit a eutectic point, and many are capable of forming hydrogen bonds when combined (Coutinho and Pinho, 2017).

DESs can be expressed using the general formula Cat^+X^-zY, where Cat^+ represents an organic cation (typically ammonium, phosphonium, or sulfonium), X^- is a Lewis base (often a halide), Y is a Brønsted or Lewis acid, and z denotes the number of Y molecules interacting with the anion. Fig. 3 shows the Cat^+X^-zY formulated classification system that helps in distinguishing the different types of eutectics (Smith et al., 2014; Abbott et al., 2007). Nowadays, type V has been added to the classification of non-ionic donors. Rafati et al. (2025) studied on Thymol-Acetamide and Thymol-Acetanilide which belong to type V DESs.

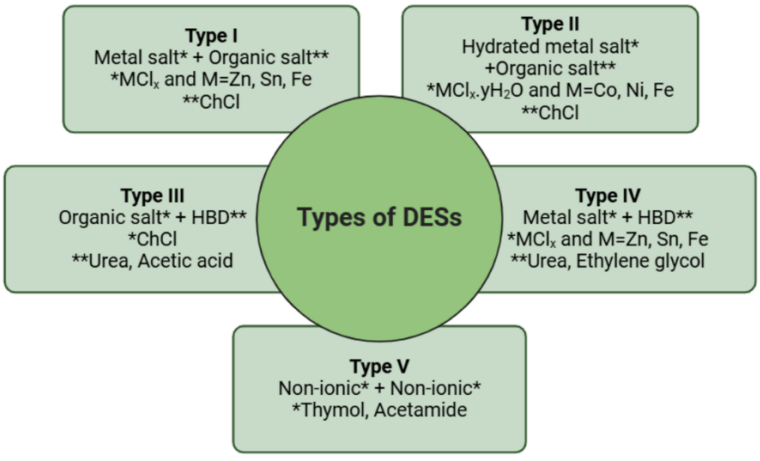

Fig. 3. Types of DESs (Smith et al., 2014, Boventi et al., 2024)

3. Advantages and limitations of DESs

DESs are widely recognized for their promising performance in diverse applications, ranging from catalysis to extraction processes. Their combination of physicochemical properties, relatively low toxicity, ease of preparation, and cost-effectiveness makes them attractive alternatives to traditional solvents (Cunha and Fernandes, 2018; Suffia and Dutta, 2024). These environmental and operational

advantages have contributed to the growing adoption interest in DESs in academic research and several chemical and materials-related processes. Fig.4(a) shows the major advantages of DESs, including thermal stability, environmental compatibility, and operational simplicity.

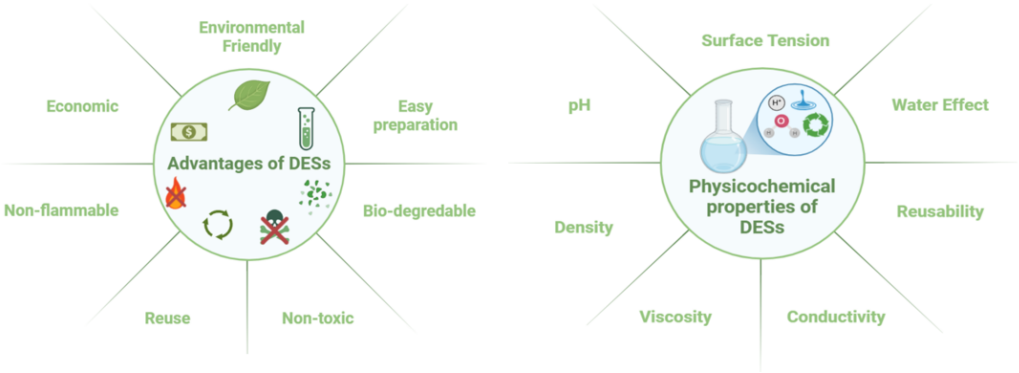

Fig. 4. (a) Key advantages and (b) physicochemical properties of DESs

The physicochemical properties of DESs are highly depended on the types and molar ratios of HBA and HBD components. According to the study by (Jablonský et al., 2019), other important factors include water content and operating temperature. Variations in the hydrogen-bond network between different components can lead to significant changes in viscosity, density, conductivity, and thermal stability, all critical parameters for metal extraction processes. Fig. 4(b) illustrates how these properties affect extraction efficiency and solvent robustness. Key attributes such as pH, density, viscosity, surface tension, water content, and reusability are discussed in further detail below. The tuneable nature of DESs allows for their customization for different extraction and separation purposes.

Despite these promising attributes, the translation of DES-based processes from laboratory research to industrial-scale metal recovery remains limited. Several constraints currently challenge their widespread adoption. First, many DES systems exhibit inherently high viscosity, which restricts mass transport and slows leaching kinetics. Consequently, elevated temperatures, the addition of controlled amounts of water, or increased mechanical agitation are often required to achieve acceptable dissolution rates.

Second, the long-term chemical stability, recyclability, and degradation pathways of DESs under industrial operating conditions are not yet fully elucidated, raising concerns regarding solvent lifetime, impurity accumulation, and overall process economics. Third, the cost, availability, and required purity of some DES components particularly specialized or high-purity HBDs may impose additional economic barriers for large-scale metallurgical use. Furthermore, industrial integration requires engineering considerations such as heat-transfer efficiency, solvent–solid contact optimization, and potential corrosion or compatibility issues with processing equipment.

A comprehensive evaluation of both the advantages and the limitations of DES-based systems is therefore critical for identifying the specific metallurgical contexts in which they can provide performance benefits over conventional hydrometallurgical reagents. Such an assessment will guide the development of optimized, energy-efficient, and economically viable DES formulations and process designs, ultimately facilitating their transition from promising laboratory solvents to robust industrial tools for sustainable metal recovery.

In addition to high viscosity, slow mass transfer, and relatively long leaching times, the chemical and thermal stability of DESs should be critically considered in metallurgical applications. This issue is particularly important for ChCl-based DESs containing carboxylic acids, which are frequently used in metal leaching studies. Rodriguez Rodriguez et al. (2019) reported that ChCl–carboxylic acid DESs may undergo degradation through esterification reactions between the carboxylic acid and the alcohol moiety of choline chloride. Therefore, such systems should not automatically be considered chemically stable under prolonged or elevated-temperature leaching conditions. Similarly, Peeters et al. (2022) showed that ChCl–ethylene glycol-based DESs can decompose at elevated temperatures, forming hazardous products such as trimethylamine and 2-chloroethanol. These findings indicate that the "green" character of DESs should be evaluated on a case-by-case basis by considering solvent

composition, operating temperature, residence time, degradation pathways, and possible toxicity of decomposition products.

Another critical issue is that leaching represents only one step in a complete metallurgical flowsheet. Although DESs can dissolve metals from solid materials, the subsequent recovery and separation of dissolved metals from loaded DESs remain challenging. Downstream operations such as precipitation, stripping, solvent extraction, electrodeposition, or the addition of external reagents may be required to recover the target metals. However, these operations can introduce new chemical species into the DES phase, alter the original solvent composition and physicochemical properties, and lead to impurity accumulation. As a result, DES recyclability may be significantly affected. Therefore, claims regarding DES reusability should be made cautiously and supported by repeated leaching–recovery cycles, solvent regeneration data, impurity monitoring, and characterization of the DES after metal recovery.

Consequently, despite the growing number of laboratory-scale studies, DES-based metal recovery has not yet reached widespread industrial implementation in metallurgy. The transition from laboratory leaching tests to industrial metallurgical practice requires not only high dissolution efficiency, but also proven solvent stability, efficient downstream metal recovery, robust solvent regeneration, acceptable process economics, and environmental validation.

4. Novel opportunities in the metal recovery areas

In recent years, the development of safer and more environmentally friendly alternatives, evaluated alongside their environmental impacts, has become a key research focus in the chemical and mining industry, particularly in ore processing and hydrometallurgy. As the industry moves towards sustainability, there is an in growing emphasis on innovative solutions that enhance efficiency while minimizing ecological footprints.

In response to the rising demand for critical raw materials and the need for safer solvents, metal recovery technologies have gained significant attention. Many studies have explored the use of DESs in separation and recovery processes, especially from secondary sources and ore leaching (Yuan et al., 2022). Conventional hydrometallurgical routes for spent lithium-ion battery cathodes commonly employ mineral acids, particularly H_2SO_4, in the presence of reducing agents such as H_2O_2 to promote the dissolution of transition-metal oxides. These systems are technologically mature and generally provide rapid dissolution kinetics. For example, Tang et al. (2022) reported that Li, Co, Ni, and Mn could be leached with efficiencies of 96.41%, 82.53%, 89.25%, and 99.99%, respectively, using 2 M H_2SO_4, 1.5 vol.% H_2O_2, a solid-to-liquid ratio of 25 g/L, 60 °C, and only 15 min of leaching. Similarly, Vieceli et al. (2023) investigated the leaching of LCO, NMC oxides, and industrial black mass using 2 M H_2SO_4 and H_2O_2; complete dissolution of several NMC oxides was achieved within 15 min, while complete Co dissolution from industrial black mass required up to 60 min under the optimized conditions of 3 vol.% H_2O_2, S/L = 1:20 g/mL, 2 M H_2SO_4, and 50 °C. In another recent study on LFP production scraps, Bruno et al. (2024) showed that selective Li leaching could be achieved using 0.25–0.5 M H_2SO_4 with 3–6 vol.% H_2O_2 at 25 °C for 1 h, reaching up to 98% Li leaching while retaining most Fe and P in the solid residue. These examples demonstrate that conventional acid-based systems can be highly efficient and, in some cases, selective when redox chemistry and operating conditions are properly controlled. However, they may also promote the simultaneous dissolution of several valuable metals and, depending on the feed composition, impurity elements such as Al, Cu, and Fe, thereby increasing the need for downstream separation. In contrast, DES-based leaching often requires longer contact times and/or higher temperatures. Nevertheless, under appropriate solvent and process conditions, DESs may enable more controlled dissolution behaviour through preferential complexation, proton-assisted dissolution, or redox-controlled dissolution of specific metal species. Therefore, DES selectivity should not be considered an inherent or universal property of all DES systems, but rather a system-dependent outcome governed by the HBA/HBD combination, molar ratio, water content, ligand coordination ability, metal speciation, redox environment, and operating conditions.

Fig. 5 illustrates the DES leaching technology and compares flow sheets used for both secondary sources and ores. These studies demonstrate the selective separation of metal oxides from various materials including recycled Li-ion batteries, permanent magnets, ores, and other metal-containing wastes. Specifically, DESs have been applied to leach Ni, Co, Li, and Mn from Li-ion batteries; Nd, Fe,

Sm, and Co from permanent magnets; and a wide range of metals from ores and materials such as anode slime, coal fly ashes, and photovoltaic panels.

4.1. Li-ion battery DES leaching

Table 1 presents DES leaching studies targeting Li-ion batteries. Most studies used ChCl as the HBA, while EG-based DESs were becoming more prominent in recent research. For instance, Tang et al. (2022) achieved highly selective leaching using EG and hydrogen donor OX dihydrate DES, reaching 94.4% Li leaching efficiency while keeping Ni, Co, and Mn leaching below 1%. Dong et al. (2023) synthesized an EG-MALO DES and studied leaching parameters such as time and solid-to-liquid ratio, achieving 100% leaching for Li, Ni, Co, and Mn. Ma et al. (2022) recycled LiCo1/3Ni1/3Mn1/3O2 cathode material using ChCl-TA DES, reporting leaching efficiencies of 96.0% Li, 97.1% Co, 98.0% Ni, and 96.7% Mn at 70 °C over 12 hours. Luo et al. (2024) used dimethyl-beta-propiothetin-EG DES, achieving 99.59% Li, 99.28% Ni, 99.04% Co, and 99.45% Mn leaching efficiencies. Chenthamara and Gardaş (2024) compared two ChCl-based DESs (pyruvic acid and glyoxylic acid monohydrate). ChCl-pyruvic acid DES achieved the highest leaching efficiency for Co and Li with 99.21% and 99.52% respectively at 80 °C in 5 hours. Zhang et al. (2024) evaluated CAA-TBAC DESs by varying key leaching parameters such as the HBA: HBD molar ratio, leaching temperature, leaching time, and solid-to-liquid ratio. While complete Co was achieved, Li recovery remained relatively low. Fig. 6 shows the effect of temperature on Co dissolution from LNCM and LCO cathode materials, with color changes observed at temperatures up to 160 °C (Fig. 6 (a)) and 130 °C (Fig. 6 (b)) (Luo et al. 2022; Wang et al. 2024). Additionally, Fig. 6 (c) demonstrates that increasing the leaching time significantly enhances Co dissolution efficiency (Wen et al. 2024).

Recently, ternary DESs were synthesized using GUC as the HBA and EG, MA, MAL, and CA as HBDs (Liu et al., 2025). The effect of molar ratios of the HBA and HBD on the leaching efficiency was studied. The optimum composition, 1 M MA, 1 M GUC and 2 M EG, achieved over 99.5% leaching efficiency for both Li and Co at 100 °C within 9 hours.

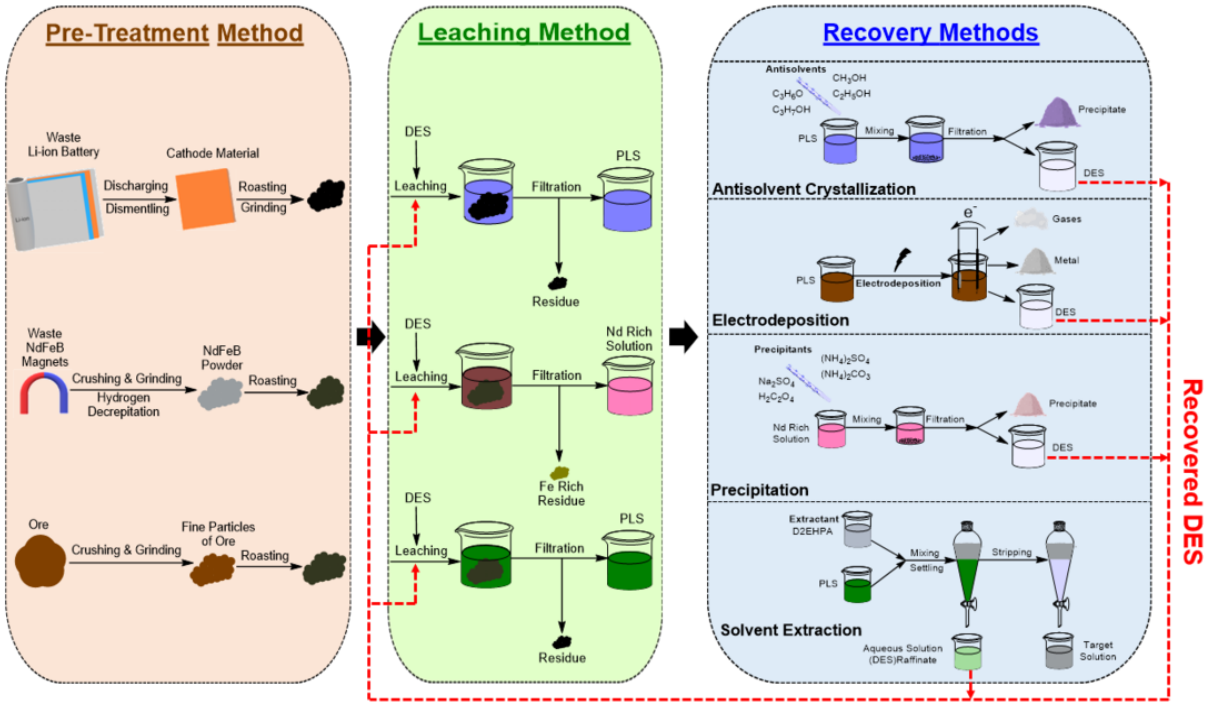

Fig. 5. Generalized flowsheets for DES-based leaching of ores and secondary resources. The schematic illustration was prepared by the authors based on the reviewed literature

4.2. Permanent magnets DES leaching

Permanent magnets, particularly NdFeB (Neodymium-Iron-Boron) magnets, are a valuable secondary resource due to their high content of rare earth and transition metals, including neodymium (Nd), iron

(Fe), and boron (B), and sometimes dysprosium (Dy) and praseodymium (Pr). Other types include Samarium-Cobalt, AlNiCo and ceramic ferrite magnets. Understanding the compositions and oxide forms of these magnets is essential for selecting appropriate recovery strategies.

Table 1. Leaching applications of end-of-life lithium-ion batteries using DESs

HBA	HBD	Cathode Material	Results	Ref.
PEG200	OX	All-solid-state LIBs	Li leaching efficiency reached 87.5% at 80 °C.	Chen et al., 2025
ChCl	LEVU	LCO and NMC111	NCM111 and LCO were leached using different ChCl-LEVU-MClx DESs. ChCl-CuCl-LAC (1:1:4) achieved 100% LCO_2 leaching with 96.3% Li and Co recovery, while NMC111 leaching efficiencies were 90.16% Li, 90.37% Co, 89.42% Mn, and 89.67% Ni.	Zhou et al., 2024
ChCl+HCl	EG	LCO	Leaching efficiency was 100%.	Yetim et al., 2024
ChCl	Tannic acid, Gallic acid, Pyrogallol	LCO and LIB	Leaching efficiency of LCO were 98% Co, %74 Li, and LIB 94.5% Co, 90% Li, 92% Mn and 93% Ni.	Sarma et al., 2024
ChCl	MALO, 2-pyrrolidinone	LCO	LCO leached with >96% efficiency.	Wen et al., 2024
ChCl	EG and Urea	Mixed of LCO, $LiMn_2O_4$, $LiNiCoAlO_2$, $LiFePO_4$	Optimal leaching rates were 92.83% Li, 1.61% Co, 0.72% Ni, and 0.42% Mn.	Jafari et al., 2022
CAA	TBAC	LCO	Co leached 100% efficiency.	Zhang et al., 2024
EG	$OX.2H_2O$	LCO and $Li_{14.8}Ni_{1.7}Co_{8.5}MnO_{3\ 0.5}$	Leaching for Li >94.4%, Ni/Mn/Co leaching 1%.	Tang et al., 2022
EG	MALO	Spent NCM523	Li, Ni, Co, Mn leached at 100% efficiency.	Dong et al., 2023
dimethyl-beta-propiothetin	EG	Spent NCM	Li, Ni, Co, and Mn leaching rates: 99.59%, 99.28%, 99.04%, 99.45%.	Luo et al., 2024
ChCl	MALO, OX, EG, CA, PEG, MAL, pTSA Propionic acid	Spent LCO	Leaching with DES using various HBD components achieved efficiencies of 98.61% for Co and 98.78% for Li.	Lu et al., 2022
ChCl	Gly	LCO	Leaching efficiency for Co was 95.7%.	Yu et al., 2022
ChCl	EG	$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	Leaching efficiencies were 89.94% Li, 100% Co, 99.64% Ni, and 100% Mn.	Wang et al., 2021
ChCl	CA, EG, OX, MALO, MAL	LCO	Leaching efficiencies of DESs with different HBD components were compared, showing 99.6% efficiency for DESs made with CA.	Peeters et al., 2020
PEG	AA	LCO	LCO material leached with 6:1 DES and leaching efficiency of Co was 84.2% at 80 °C, 72 h.	Chen et al., 2023

ChCl	MAL, Gly	Spent NCM	Battery leached with 1:1:3 ChCl: Mal: Gly DESs at 130 °C and 60 g/L with 94.6% Ni, 96.8% Co, 93.8% Mn, and 96.4% Li efficiencies.	Zheng et al., 2024
TEAC	AA	Spent LNCM	NCM battery leached with 99.1%, 99.6%, 99.4% and 99.3% for Li, Ni, Co, and Mn, respectively at 80 °C, 3 min.	Zhang et al., 2024
D-Glucose	LAC	LFP	LFP cathode material leached selectively with 96.5% Li efficiency.	Chen et al., 2024
hydroxyl-amine hydrochloride	EG	LCO	$LiCoO_2$ leached with 4:1 DES and leaching efficiencies reached 99.7% and 88.0% for Li and Co, respectively at 80 °C for 8 h.	Zhou et al., 2024
ChCl	AC	NCM111	Li, Mn, Co and Ni were leached with 97.1%, 93.3%, 96.5% and 96.1% efficiencies, respectively.	Lyu et al., 2024
ChCl	pTSA, EG	NMC	Ternary DESs (TCE) 1:1:1 and 0.5:1:1. Leaching efficiencies for both DESs were 100% Li, 98.2% Ni, 97.8% Mn, 96.1% Co and 99.4%Li, 100% Ni, 100% Mn, 99.4% Co, respectively.	Xu et al., 2024
ChCl	$CA.H_2O$	LCO	Li and Co leaching efficiencies reached 100% and 97.6%, respectively.	Wang et al., 2024
dimethyl-beta-propiothetin chloride	AA	LNCM111	Li, Ni, Co and Mn leached with 99% leaching efficiency.	Li et al., 2025
CAA	Ethanol	LFP	Li leaching efficiency was 100% while Fe leaching efficiency was less than 0.3%.	Zhang et al., 2025
ChCl	OX, H_2O	LFP	Li and Fe leaching efficiencies reached 99.96% and 99.95% respectively.	Zhang et al., 2025
ChCl	EG	LCO	Co leached completely with 1:5 ChCl:EG DES.	Shahid et al., 2025
EG	CA, Ethanol	LCO and $Li_{3.2}Ni_2.3Co_{0.9}Mn_{1.4}O_{6.3}$	Under optimal conditions, the leaching efficiency of Li was greater than 94.4% in the filtrates of $LiCoO_2$ and $Li_{3.2}Ni_{2.3}Co_{0.9}Mn_{1.4}O_{6.3}$, while more than 84.6% of Ni, 85.5% of Co, and 47.4% of Mn were successfully separated.	Guo et al., 2025
ChCl	GA, AA	Mixed of LCO, $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ and $LiMn_2O_4$	Leaching efficiency reached to over 95% for each metal Li, Co, Ni and Mn by using ternary DES of ChCl:GA:AA with 1:1.9:0.1 molar ratio.	Nazlı et al., 2025

Recent studies have reported successful applications of DES leaching for rare earth magnets (Table 2). The roasted NdFeB magnets (950 °C, 15 h) were leached using ChCl-SA DES at 60 °C for 24 h, achieving 97% Nd recovery (Varghese et al., 2024). Shuping et al. (2025) also compared four DESs (TEAC as HBA and LEVU, MALO, LAC, and GA as HBDs), achieving 97.63% Nd and 0.435% Fe leaching. Yang et al. (2024) used citric acid, MA, and 1,2-malonate as HBAs, with EG, glycerin, and 1,2-propanediol as HBDs. After oxidative roasting at 800 °C – 1000 °C, the optimum Nd and Fe leaching efficiencies were 28.07% and < 0.01%, respectively.

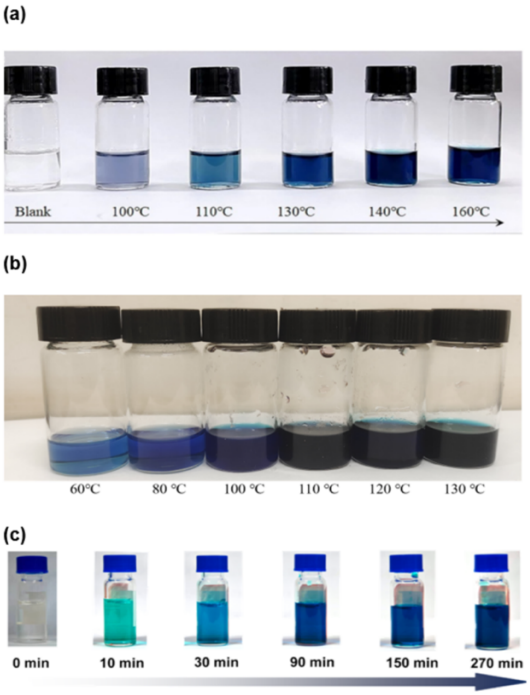

Fig. 6. (a) Effect of temperature on LNCM battery dissolution (Luo et al., 2022); (b) LCO dissolution in DES at various temperatures (Wang et al., 2024); (c) Leaching time effect on Co dissolution efficiency (Wen et al., 2024)

Heo et al. (2024) employed a comprehensive three-step approach to ensure complete oxidation of NdFeB magnets prior to leaching. First, the material caustic digestion using 50% NaOH at 145 °C for 5 h under atmospheric conditions. This was followed by oxidation roasting at 450 °C for 3 h to convert the magnets fully into oxide form. Finally, the oxidized material was leached using EG-MA DES, achieving leaching efficiencies of 97% for Nd and 0.7% for Fe.

Furthermore, the DES was successfully recovered and reused for two additional leaching cycles without any significant loss in performance, demonstrating its recyclability. A comparison between the studies of Yang et al. (2024) and Heo et al. (2024) reveals that although both used the same EG-MA DES, their leaching efficiencies differed significantly due to the oxidation states of the material. Yang et al. were unable to achieve full oxidation, resulting in lower Nd recovery, whereas Heo et al. employed a more effective caustic digestion that led to complete oxidation and improved leaching performance. These findings emphasize the critical role of pre-treatment and oxidation in enhancing the selectivity and efficiency of DES-based leaching processes.

4.2. Efficient ore leaching with DESs

Several studies have investigated the application of DESs in leaching metal ores and concentrates (Table 3). Winardhi et al. (2022) leached sulfide concentrate using ChCl-EG DES, 91.7% Au, 62.6% Ag, and 96.4% Te recovery after 96 h. Anggara et al. (2019) tested various DESs (ChCl with EG, urea, OX) for copper ores, reaching 99% Cu recovery.

Shakiba et al. (2023) leached roasted monazite concentrate (500 °C for 2 h, NaOH pretreatment) using ChCl-NaOH-PEG400 DESs, achieving 99.8% Ce, 99.9% La, and 94% Nd recovery. ChCl-LAC and pTSA DESs achieved 95% REE leaching from microgranite-type primary hard rock containing rare earth metals (Karan and Sreenivas, 2023). Sudová et al. (2024) applied ChCl-EG, ChCl-MALO, and ChCl-thiourea DESs for antimony leaching from flotation waste. Among the DESs tested, ChCl-EG exhibited the highest leaching performance with 74.15% Sb recover at 100 °C after 4 hours. In contrast, ChCl-MALO DES showed a lower efficiency of 25.05% under the same temperature but after 24 hours, while ChCl-thiourea DES achieved a slightly higher efficiency of 25.97% at 80 °C after 24 hours. This comparison highlights the significant effect of both the HBD type and leaching conditions on antimony recovery. To enhanced the leaching performance, 3 grams of iodine were used as an oxidizing agent, enabling ChCl-EG DES to reach 100% Sb leaching efficiency. Iodine, due to its ability to accept electrons, act as a reducing agent. Although iodine-assisted oxidation it is not yet a widely

adopted industrial-scale processes, its effectiveness in enhancing metal recovery has been demonstrated. Additionally, hypervalent iodine compounds have gained attention for their friendly oxidizing potential in organic synthesis, showing promise for broader application in sustainable hydrometallurgical practices (Shetgaonkar et al., 2023).

Table 2. Recovery of rare earth elements from permanent magnets using DESs

HBA	HBD	Results	Ref.
GUC	LAC	After selective leaching with synthetic DES, Nd was precipitated as $Nd_2(C_2O_4)_3$ with OX, and then converted to Nd_2O_3 by calcination, achieving 99% recovery of NTE oxide.	Liu et al., 2020
ChCl	LAC	Roasted residual magnet (<100 microns) was selectively leached at 70 °C for 24 hours, separating Co, Fe, and B from Nd and Dy. Nd and Dy were precipitated with OX and calcined at 950 °C for 3 hours, yielding Nd_2O_3 (99.87% purity) and Dy_2O_3 (99.94% purity).	Riaño et al., 2017
Tri-octylphosphane oxide	Dodecanol	Sm and Fe leaching efficiencies reached above 99%.	Ni et al., 2021
EG	MA	NaOH digestion and oxidative roasting at 450°C for 3 hours were applied. After leaching with EG-MA DES, efficiencies of 97.3% for Nd and 0.8% for Fe were achieved. Recycling the DES and leaching with the recycled DES resulted in 97% efficiency for Nd and 0.7% for Fe.	Heo et al., 2024
TEAC	LEVU, MALO, LAC, GA	DESs' characteristic features were observed. The leaching efficiency for Nd was 97.63% and for Fe was 0.435%.	Shuping et al., 2025
Trioctylphosphine Oxide	Decan-1-ol, Lauryl alcohol, Myristyl alcohol	Ternary HDES determined as DA: MA: Trioctylphosphine Oxide, 5: 5: 4 and recovery reached 99% with the final product purity was over 99%.	Yu et al., 2024
ChCl	SA	Grinding was applied to the demagnetized magnets, which were then roasted at 950°C for 15 h. The roasted magnets were leached for 24 hours at 60 °C and 200 rpm, achieving a maximum leaching efficiency of 97%.	Varghese et al., 2024
Citric acid, MA and 1,2-Malonate	EG, Glycerin and 1,2-propanediol	Nd and Fe leaching efficiencies reached 28.07% and 0.01%, respectively.	Yang et al., 2024
ChCl	MALO	NaOH digestion and roasting at 450 °C for 3 h were applied. After that roasted magnet leached with ChCl-MALO DES at 80 °C for 6 h with 1:20 S/L ratio. Leaching efficiencies reached 95.5 and 1% for Nd and Fe, respectively.	Yadav et al., 2025
ChCl	OX, EG and Urea	ChCl-OX DES combination is selected as optimum with 14% Sm and 82% Co leaching efficiencies.	Nasrullah et al., 2025

Table 3. Application of DESs in ore leaching

Ore	HBA	HBD	Results	Ref.
Bastnasite	$FeCl_3$	EG	The highest light rare earth elements leaching efficiency reached 75.98%.	Kaplan et al., 2025
Electrum (Au and Ag)	ChCl+0.1 mol Iodine	EG	Leaching efficiencies for electrum was 100%.	Winardhi et al., 2022
Sulfide concentrate that bearing Ag, Te, Au, Pb, Cu	ChCl	EG	Optimum leaching efficiencies for Au, Ag and Te were 91.7%, 62.6%, and 96.4%, respectively.	Winardhi et al., 2022
$CuFeS_2$, CuS and Cu_2S	ChCl	EG, Urea, OX dihydrate	Leaching efficiency reached 99%.	Anggara et al., 2019
Caustic treated monazite concentrates	ChCl, NaOH, PEG-400	Urea, EG, PEG200, PEG400, pTSA, AC, LAC	Leaching efficiencies of Ce, La and Nd reached 99.8%, 99.9%, and 94%, respectively.	Shakiba et al., 2023
Rich microgranite type primary hard rock REE	ChCl	LAC and pTSA monohydrate	REE leaching efficiency reached 95%.	Karan et al., 2023
Antimony from Mining Residue	ChCl	EG, MALO and Thiourea	Leaching efficiency for each different HBD group were 74.15%, 25.05%, and 25.97%. By using iodine, leaching efficiency reached 100% for Ethaline.	Sudová et al., 2024
Cu, Fe, Pb, Zn bearing oxides, sulfates and sulphides	ChCl	EG, Urea and Gly	Reline, Ethaline and Glyceline synthesized, sulfates leaching behaviour were higher than oxides and sulfides.	Aragón-Tobar et al., 2024
Chalcopyrite concentrate ($CuFeS_2$)	ChCl, pTSA	OX, EG, Sucrose, MALO, Fructose, Urea, MA, CAand Glucose	The highest leaching efficiency for copper was 90.5% with ChCl: pTSA DES.	Moradi et al., 2024
Chalcopyrite concentrate ($CuFeS_2$)	$FeCl_3$	EG	For economic process leaching efficiency for chalcopyrite reached 87%.	Li et al., 2020
Chalcopyrite concentrate ($CuFeS_2$)	ChCl	Urea and MA	The highest leaching efficiency for copper was 48% with ChCl: MA DES.	Mohammad pour et al., 2024
Sphalerite (Zns) concentrate	ChCl, pTSA	EG	Leaching efficiency of Zinc reached 99.7%.	Shahrezaei et al., 2024
Sphalerite (Zns)-Galena (PbS) concentrate	ChCl	Urea, EG and Gly	The highest Zn and Pb leaching efficiencies were 99% for both metal with combining roasting pre-treatment method.	Moreno et al., 2024
Pyrite (FeS_2)	ChCl	EG	Fe leaching efficiency was 23.6%.	Teimouri et al., 2023

Chalcopyrite	ChCl	EG, OX	The highest copper leaching efficiency reached 76%.	Ghadamgahi et al., 2025
Cu-Co Ore	ChCl	OX	The highest Cu and Co leaching efficiencies reached 92.4% and 90.6%. By using H_2O_2, leaching efficiencies increased to 100% and 97.5%, respectively.	Oke et al., 2025
Chalcopyrite concentrate	ChCl	EG, OX, MALO	The highest leaching efficiency for Cu reached to 54% with using ChCl-EG-OX ternary DES with 1:2:1 ratio. By adding water 20% volume, leaching efficiency increased to 86%.	Shiri et al., 2025
Chalcopyrite concentrate	ChCl	pTSA, MALO	Optimum leaching efficiency reached to 83.9% and 87.2% for Cu and Fe respectively with using 1:1:1 molar ratio of ternary DES of ChCl:MALO:pTSA.	Moradi et al., 2025

4.3. Other secondary resources DES leaching

Please submit tables as editable text and not as images. Tables should be placed next to the relevant text in the Recent studies have demonstrated the effective application of DES leaching for extracting valuable metals from secondary resources such as waste printed circuit boards (WPCBs), coal fly-ash, and metallurgical slags (Table 4). For instance, Topçu et al. (2021) recovered Cu and Ag with efficiencies of 97% and 91.02%, respectively, from anode slime using ChCl-Urea and EG DESs, while investigating the effects of leaching parameters such as time, temperature, solid-to-liquid ratio, and water content. Zhang et al. (2022) reported 98% Ag extraction from photovoltaic panels using ChCl-Urea DES. Niu et al. (2022) applied ChCl-Urea DES to zinc-containing dust sludge, optimizing leaching time, temperature, liquid-to-solid ratio, stirring rate, and ultrasonic power. Under optimum conditions, 60 °C, 240 minutes, a 12:1 liquid-to-solid ratio, and 350 W ultrasound, Zn recovery reached 98%. Karan et al. (2022) investigated coal clay fly-ash leaching using ChCl¬-pTSA and ChCl-LAC DESs, with the highest metal recovery of 95% observed using a 1:1 ChCl-pTSA ratio. Topçu et al. (2021) further utilized ChCl-Urea DES to leach copper converter slag, 90% Cu and 65% Zn recovery.

Mishra et al. (2024) compared several ChCl-based DESs (with urea, EG, MALO, FA, and OX) for mobile phone PCBs. Their multistage leaching process, initiated with 1 M OX DES at 80 °C, in 1 hour (300 rpm, 1/20 g/mL), extracted over 93% Sn and was visualized in a process flow chart (Fig. 7). The study emphasized that oxidized metals form coordination complexes with the chloride (Cl-) or carboxyl (COOH-) groups of DESs, which enhances metal extraction. Additionally, the presence of C=O stretching vibrations in PCBs facilities further interaction with DESs, thereby improving leaching performance. Bakkar (2014) used ChCl-Urea DES to leach electric arc furnace dust, achieving 60% Zn and 39% Pb recovery. Zürner and Frisch (2019) synthesized ChCl-EG, ChCl-urea, and ChCl-OX DESs for the leaching of zinc flue dust. While Ethaline (ChCl-EG) and Reline (ChCl-urea) showed very low leaching efficiencies of indium and tin at 50°C and 48 hours, Oxaline (ChCl-OX) demonstrated significantly higher performance, yielding 92% indium and 88% tin recovery.

5. Conclusions

The present review highlights the significance of DESs in the leaching and recovery of critical and rare metals from both primary and secondary metal-bearing resources. Literature studies show that DESs can provide selective metal dissolution in several systems, enabling efficient target metal recovery and reducing the need for extensive downstream purification in selected applications. In this context, DES-based leaching represents a promising alternative to conventional mineral acid leaching, particularly for complex matrices such as spent lithium-ion batteries, permanent magnets, waste printed circuit boards, coal fly ash, metallurgical slags, red mud, and primary ores. The scientific contribution of this review is its integrated evaluation of DES-based metal recovery from a mineral processing perspective, with emphasis on physicochemical properties, solvent composition, selectivity, operating conditions, process flowsheets, downstream recovery, and practical implementation challenges.

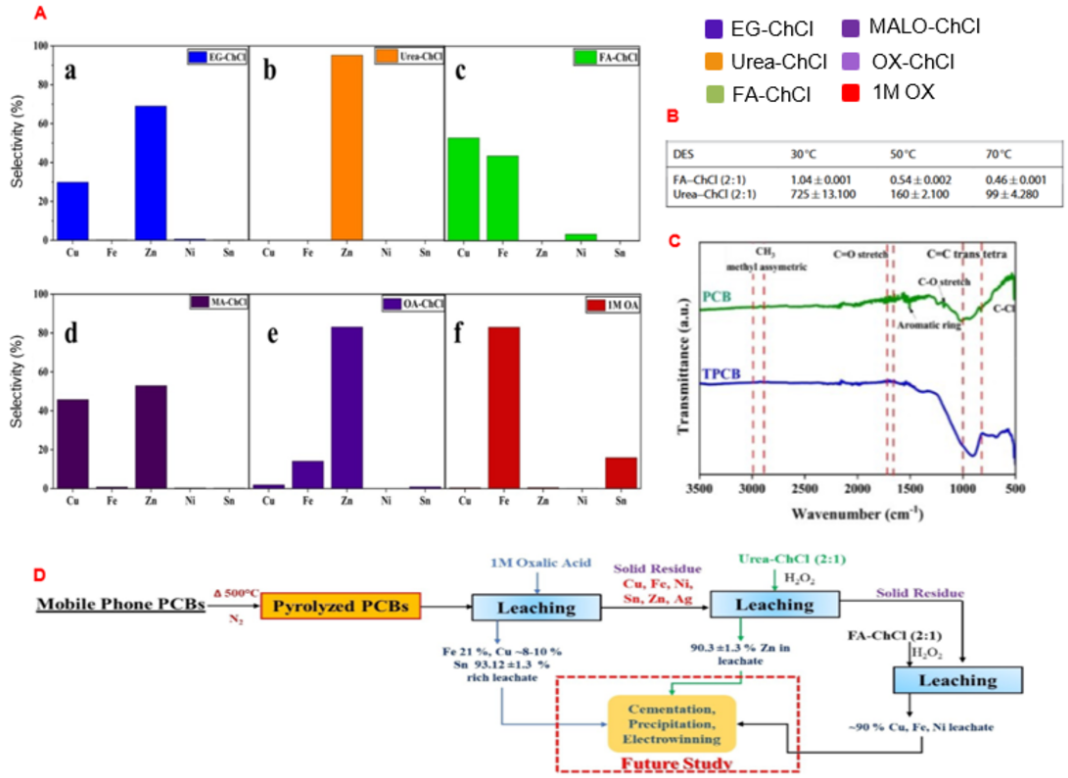

Fig. 7. ChCl based DESs for the selective metal extraction from thermally treated mobile phone PCBs; (A) metal recovery; (B) viscosity vs. temperature; (C) FTIR analysis; (D) suggested leaching flowchart. Reproduced from (Mishra et al., 2024)

Table 4. DES leaching examples for various secondary resources.

Material	HBA	HBD	Results	Ref.
Anode slime	ChCl	Urea and EG	Leaching efficiency of Cu and Ag reached 97% and 91.02%, respectively.	Topcu et al., 2021
Photovoltaic panel	ChCl	Urea	The highest leaching efficiency was 98%.	Zhang et al., 2022
Zinc-containing dust sludge	ChCl	Urea	Optimum leaching efficiency of Zn was 98%.	Niu et al., 2022
Coal fly ash	ChCl	pTSA and LAC	Highest leaching efficiency reached 95%.	Karan et al., 2022
Copper converter slag	ChCl	Urea	The highest Cu and Zn leaching efficiencies were 90% and 65%.	Topçu et al., 2021
WPCBs	ChCl	FA, Urea, OX EG, MALO	Selective extraction; ~90 % of copper, iron, and nickel in FA-ChCl, while ~90 % zinc extraction in Urea-ChCl	Mishra et al., 2024
Electric arc furnace powder	ChCl	Urea	Zn and Pb leaching efficiencies were 60% and 39%, respectively.	Bakkar, 2014
Zinc flue dust	ChCl	EG, urea, OX	Indium and Tin leaching efficiencies reached 92% and 88%, respectively.	Zürner and Frisch, 2019

Spent automotive catalysts	ChCl+HNO_3	Urea, EG, PEG-200, PEG 400, pTSA, AC, DL-LAC	Pt, Pd and Rh leaching efficiencies were 100%, 100%, and 50%, respectively.	Lanaridi et al., 2022
WPCBs	ChCl	EG, OX, GA	ZnO leaching efficiency reached 90%. Other oxides leaching efficiencies lower than 22%.	Zhao et al., 2023
Sodium-ion battery	PEG200	AA, Phenol, EG, Benzamide, Choline iodide, N-methyl-acetamide	Cathode material leached by different DESs and maximum leaching efficiency for Na was 88.3% with 10:1 PEG: AA DES.	Chen et al., 2025
Waste smelting slag	ChCl	Urea	80% Cu and 61% Zn leached with 1:2 DES	Topçu et al., 2024
Cold filter cake	ChCl	EG, OX, CA, MALO, Urea and MA	The highest cadmium leaching efficiency reached 97.47%.	Jafari-Basirabad et al., 2024
WPCBs	ChCl, TMA, GuHCl	EG, Gly, OX and FA	ChCl-H_2O_2-EG DES used to leached Cu and leaching efficiency was 97.8%.	Liu et al., 2024
Copper smelter slag	TBAC	CA	Cu, Zn and Fe leached with 77%, 49%, and 1%, respectively.	Mohammad et al., 2024
Residual lead automotive battery recycling slag	ChCl	Glycerine	Pb leaching efficiencies reached 95%.	Salgado et al., 2024
PCBs	ChCl	Urea, LAC, OX, EG, MAL, FA	By using H_2O_2, leaching efficiency of Cu reached over 80% when 1:2 DES to water mixed	Emmons-Burzyńska et al., 2025
WPCBs	ChCl	EG, LEVU, MALO, AC, CA, Iodine	Cu, Ni, Au, Fe and Al leached with 99%, 92%, 90%, 40%, and 0% respectively.	Saffaj et al., 2025
Waste phosphors	ChCl	MALO	By using ultrasound, leaching efficiency reached to 90.13%.	Li et al., 2025
Waste phosphors	ChCl	MALO	Leaching efficiency reached to 95.7% for yttrium.	Li et al., 2025
Red mud	ChCl	OX, EG, Urea	The highest metal dissolution from red mud provided with ChCl-OX DES combination with 76.8% vanadium and 84.2% titanium.	Rüşen et al., 2026

One of the key advantages of DESs is their tunable nature, which allows their physicochemical properties to be adjusted through the selection of hydrogen bond acceptor and hydrogen bond donor combinations, molar ratio, water content, and operating temperature. This tunability provides opportunities for improving metal dissolution, enhancing selectivity, and reducing the use of aggressive mineral acids in selected separation and extraction applications. DESs may also contribute to more sustainable hydrometallurgical processes by lowering chemical consumption, reducing hazardous effluent generation, and supporting circular resource utilization through the recovery of valuable

metals from secondary resources. Moreover, the potential regeneration and reuse of DESs, when properly demonstrated through repeated leaching–recovery cycles, may help reduce reagent consumption and the environmental footprint of metal recovery processes.

However, replacing conventional mineral acids with DESs in industrial leaching processes still presents several challenges. Long leaching durations, high operating temperatures, high viscosity, slow mass transfer, solvent degradation, impurity accumulation, and downstream metal recovery remain important limitations. Although several studies have reported selective dissolution in DES-based leaching, the mechanistic origin of this selectivity is still not fully resolved in many cases. Therefore, future studies should focus not only on reporting leaching efficiencies, but also on clarifying the roles of solvent composition, metal speciation, complexation, redox chemistry, water content, and operating conditions in governing selective metal dissolution.

Several recent patents also indicate increasing technological interest in the use of DESs for metal extraction and recovery. Patent EP3596241B1 (European Patent Office, 2023) describes a method for recovering rare earth elements from metallic or alloyed sources using specially designed DES formulations, highlighting the relevance of DESs for high-value materials such as permanent magnets and rechargeable batteries. Similarly, patent US20200399737A1 (United States Patent Office, 2020) focuses on the dissolution of metal oxides using DESs, emphasizing their potential for selective metal extraction and solvent recovery. In addition, patent CN117940592A (China National Intellectual Property Administration, 2024) presents a hydrophobic DES-based leaching system aimed at improving phase separation and optimizing downstream processing. These patent examples suggest a growing trend toward tailoring DES compositions for specific metal recovery applications. However, they should be interpreted as emerging commercialization signals rather than evidence of mature industrial implementation.

Despite these promising advancements, the large-scale industrial implementation of DES-based leaching remains limited by challenges related to solvent stability, recyclability, downstream metal recovery, process integration, scalability, environmental validation, and economic viability compared with traditional hydrometallurgical methods. Future research should therefore move beyond single-step leaching performance and systematically evaluate DES degradation, post-leaching solvent composition, impurity accumulation, solvent regeneration efficiency, environmental impact, and repeated leaching–recovery cycles under realistic process conditions. By addressing these knowledge gaps, DES-based processes may become more practical and sustainable tools for critical and rare metal recovery.

Acknowledgments

This research was funded by the Scientific Research Projects Coordination Unit (BAP) of Istanbul Technical University under grant number MGA-2023-45070. The authors also acknowledge support from the Scientific and Technological Research Council of Türkiye (TÜBİTAK) through the 1001 Program, grant number 123M564.

Abbreviations

DESs	Deep Eutectic Solvents
DES	Deep Eutectic Solvent
ILs	Ionic Liquids
HBA	Hydrogen Bond Acceptor
HBD	Hydrogen Bond Donor
ChCl	Choline Chloride
GUC	Guanidine Hydrochloride
pTSA	p-toluenesulfonic Acid
TBAC	Tetrabutylammonium Chloride
TEAC	Tetraethylammonium Chloride
TMA	Trimethylammonium Chloride
AA	Ascorbic Acid
EG	Ethylene Glycol

PEG Polyethylene Glycol
CA Citric Acid
MALO Malonic Acid
MA Maleic Acid
MAL Malic Acid
OX Oxalic Acid
AC Acetic Acid
FA Formic Acid
TA Tartaric Acid
SA Salicylic Acid
GA Glycolic Acid
CAA Chloroacetic Acid
LEVU Levulinic Acid
Gly Glycerol
LAC Lactic Acid
NADE Natural Deep Eutectic Solvents
MDESs Magnetic Deep Eutectic Solvents
HREEs Heavy Rare Earth Elements
HDES Hydrophobic Deep Eutectic Solvent
LCO Lithium Cobalt Oxide
FTIR Fourier Transform Infrared Spectroscopy
LNCM Lithium Nickel Cobalt Manganese Oxide
NMC Nickel Manganese Cobalt
NdFeB Neodymium-Iron-Boron
REE Rare Earth Element
REEs Rare Earth Elements
WPCBs Waste Printed Circuit Boards
PCBs Printed Circuit Boards

References

ABBOTT, A.P., BARRON, J.C., RYDER, K.S., WILSON, D., 2007. *Eutectic-based ionic liquids with metal-containing anions and cations*, Chem. Eur. J. 13(22), 6495–6501.

ABBOTT, A.P., CAPPER, G., DAVIES, D.L., RASHEED, R.K., TAMBYRAJAH, V., 2003. *Novel Solvent Properties of Choline Chloride/Urea Mixtures*, Chem. Commun. (1), 70-71.

ACHKAR, T.E., FOURMENTIN, S., GREIGE-GERGES, H., 2019. *Deep Eutectic Solvents: An Overview on Their Interactions with Water and Biochemical Compounds*, J. Mol. Liq. 288, 111028.

AN, Z., ZHAO, Y., ZHANG, Y., 2023. *Mineral Exploration and the Green Transition: Opportunities and Challenges for the Mining Industry*, Resources Policy 86, 104263.

ANGGARA, S., BEVAN, F., HARRIS, R.C., HARTLEY, J.M., FRISCH, G., JENKIN, G.R., ABBOTT, A.P., 2019. *Direct extraction of copper from copper sulfide minerals using deep eutectic solvents*, Green Chem. 21(23), 6502–6512.

ARAGÓN-TOBAR, C.F., ENDARA, D., DE LA TORRE, E., 2024. *Dissolution of metals (Cu*, Fe, Pb, and Zn) from different metal-bearing species (sulfides, oxides, and sulfates) using three deep eutectic solvents based on choline chloride, Molecules 29(2), 290.

BAKKAR, A., 2014. Recycling of electric arc furnace dust through dissolution in deep eutectic ionic liquids and electrowinning, J. Hazard. Mater. 280, 191–199.

BOVENTI, M., MAURI, M., CASTIGLIONE, F., SIMONUTTI, R., 2024. *Exploring the Structure of Type V Deep Eutectic Solvents by Xenon NMR Spectroscopy*, Faraday Discuss.

CHEN, F., ZHANG, C., YANG, C., JU, X., ZHANG, Z., LIU, Z., YANG, M., 2024. *Efficient and Selective Dissolution of Li from Lithium-Ion Battery $LiFePO_4$ Cathode by Natural Deep Eutectic Solvents*, Energy Fuels 38(6), 5391–5396.

CHEN, Y., SHEN, Y., SHI, Z., ZHANG, Z., ZHANG, Q., WANG, Y., WANG, C., 2025. *Recovery of all-solid-state sodium-ion batteries cathode and solid electrolyte using deep eutectic solvents as green solvents*, Sep. Purif. Technol. 359, 130473.

CHEN, Y., SHI, Z., ZHANG, X., WANG, C., WANG, Y., NIU, Z., FENG, M., 2025. *Recycling Solid Electrolytes from All-Solid-State Lithium-Ion Batteries by Using Deep Eutectic Solvents as Green Extractants*, ChemSusChem e202402126.

CHEN, Y., WANG, Y., BAI, Y., FENG, M., ZHOU, F., LU, Y., MU, T., 2023. *Mild and efficient recovery of lithium-ion battery cathode material by deep eutectic solvents with natural and cheap components*, Green Chem. Eng. 4(3), 303–311.

CHENTHAMARA, B., GARDAS, R.L., 2024. *Beyond the Conventional Leaching: Exploring Pyruvic Acid-Based Deep Eutectic Solvents for Sustainable Recycling of Spent Lithium-Ion Battery Cathode Material*, ACS Sustainable Chem. Eng. 12(34), 12827–12836.

CUNHA, S.C., FERNANDES, J.O., 2018. *Extraction Techniques with Deep Eutectic Solvents*, TrAC Trends Anal. Chem. 105, 225–239.

DONG, L., LI, Y., SHI, P., REN, Z., ZHOU, Z., 2023. Low-viscosity acidic deep eutectic solvent for extraction of valuable metals from spent NCM, J. Power Sources 582, 233564.

EMMONS-BURZYŃSKA, M., JĘDRZEJCZAK, E., PIASECKI, A., ŁAWNICZAK, Ł., REGEL-ROSOCKA, M., WYSOKOWSKI, M., 2025. *Leaching of metals from electronic waste using carboxylic acid-based deep eutectic solvents: Preliminary laboratory studies and molecular modelling*, Hydrometallurgy 106465.

GHADAMGAHI, S.M., BABAKHANI, A., BARATI DARBAND, G., SHALCHIAN, H., BEHMADI, R., 2025. *Solvometallurgical properties of choline chloride-based deep eutectic solvents for copper extraction from chalcopyrite: Optimization and analysis*, Mining 5(1), 8.

GUO, M., SU, R., TANG, S., WANG, Y., ZHANG, M., 2025. *Ethanol-driven bifunctional deep eutectic solvents for efficient in situ selective recovery of valuable metals from spent lithium batteries*, Sep. Purif. Technol. 132577.

HANSEN, B.B., SPITTLE, S., CHEN, B., POE, D., ZHANG, Y., KLEIN, J.M., et al., 2020. Deep eutectic solvents: A review of fundamentals and applications. Chemical Reviews 121(3), 1232–1285.

HEO, S., KIM, R., YOON, H.S., KIM, C.J., CHUNG, K.W., LEE, S., 2024. *Effect of pretreatment methods on the selective leaching of rare earth elements from NdFeB permanent magnets using deep eutectic solvents*, Hydrometallurgy 226, 106284.

JABLONSKÝ, M., ŠKULCOVÁ, A., ŠIMA, J., 2019. *Use of Deep Eutectic Solvents in Polymer Chemistry–A Review*, Molecules 24(21), 3978.

JAFARI-BASIRABAD, M., BEHNAJADY, B., OJAGHI-ILKHCHI, M., 2024. *Selective leaching of cadmium from cold filter cake using green deep eutectic solvent choline chloride–oxalic acid*, JOM 1–10.

JAFARI, M., SHAFAIE, S.Z., ABDOLLAHI, H., ENTEZARI-ZARANDI, A., 2022. *Green recycling of spent Li-ion batteries by deep eutectic solvents (DESs): Leaching mechanism and effect of ternary DES*, J. Environ. Chem. Eng. 10(6), 109014.

JENKIN, G.R., AL-BASSAM, A.Z., HARRIS, R.C., ABBOTT, A.P., SMITH, D.J., HOLWELL, D.A., et al. 2016. *The Application of Deep Eutectic Solvent Ionic Liquids for Environmentally-Friendly Dissolution and Recovery of Precious Metals*, Miner. Eng 87, 18-24.

KAPLAN, S.S., KURTULAN, C.C., GURMEN, S., ORHAN, G., SONMEZ, M.S., 2025. *Influence of Calcination Conditions on Deep Eutectic Solvents (DES) Leaching Efficiency of Light Rare Earth Elements in Bastnasite Ore*, Miner. Eng. 220, 109087.

KARAN, R., SREENIVAS, T., 2023. *Recovery of rare earth values from micro-granite type hard rocks using deep eutectic solvents*, Trans. Indian Inst. Met. 1–11.

KHAN, H. W., NEGASH, B. M., ZULKIFLY, N. I., WIZRAL, M. D. H., JAMIL, A. H. A., MISHRA, S., DAIN, C. (2026). *Deep eutectic solvents as an emerging sustainable solvent for the separation and recovery of rare earth elements: current challenges and future prospectives*. Minerals Engineering, 237, 110051.

LANARIDI, O., PLATZER, S., NISCHKAUER, W., BETANZOS, J.H., ITURBE, A.U., DEL RIO GAZTELURRUTIA, C., BICA-SCHRÖDER, K., 2022. *Benign recovery of platinum group metals from spent automotive catalysts using choline-based deep eutectic solvents*, Green Chem. Lett. Rev. 15(2), 405–415.

LI, B., LI, C., WANG, J., WAN, R., CHEN, J., LIU, Y., JU, S., 2025. *High-efficiency leaching of valuable metals from waste lithium-ion ternary batteries under mild conditions using green deep eutectic solvents*, Green Chem. 27(1), 163–178.

LI, B., LI, C., WANG, J., WAN, R., CHEN, J., LIU, Y., ZHANG, Z., BIN, Y., YANG, X., BAO, C., JU, S., 2024. *High-efficiency leaching of valuable metals from waste lithium-ion ternary batteries under mild conditions using green deep eutectic solvents*. Green Chemistry 27(1), 163–178.

LI, X., MONNENS, W., LI, Z., FRANSAER, J., BINNEMANS, K., 2020. *Solvometallurgical process for extraction of copper from chalcopyrite and other sulfidic ore minerals*, Green Chem. 22(2), 417–426.

LIU, C., YAN, Q., ZHANG, X., LEI, L., XIAO, C., 2020. *Efficient Recovery of End-of-Life NdFeB Permanent Magnets by Selective Leaching with Deep Eutectic Solvents*, Environ. Sci. Technol. 2020, 54(16), 10370-10379.

LIU, K., WANG, M., ZHANG, Q., DUTTA, S., ZHENG, T., VALIX, M., TSANG, D.C., 2024. *Negative-carbon recycling of copper from waste as secondary resources using deep eutectic solvents*, J. Hazard. Mater. 465, 133258.

LU, B., DU, R., WANG, G., WANG, Y., DONG, S., ZHOU, D., LI, C., 2022. *High-efficiency leaching of valuable metals from waste Li-ion batteries using deep eutectic solvents*, Environ. Res. 212, 113286.

LUO, Y., DENG, Y., SHI, H., YANG, H., YIN, C., OU, L., 2024. *Green and efficient recycling method for spent Ni–Co–Mn lithium batteries utilizing multifunctional deep eutectic solvents*, J. Environ. Manage. 351, 119814.

LUO, Y., YIN, C., OU, L., ZHANG, C., 2022. *Highly efficient dissolution of the cathode materials of spent Ni–Co–Mn lithium batteries using deep eutectic solvents*, Green Chem. 24(17), 6562–6570.

LYU, Y., YUWONO, J.A., FAN, Y., LI, J., WANG, J., ZENG, R., GUO, Z., 2024. *Selective Extraction of Critical Metals from Spent Li-Ion Battery Cathode: Cation–Anion Coordination and Anti-Solvent Crystallization*, Adv. Mater. 2312551.

MA, C., SVÄRD, M., FORSBERG, K., 2022. *Recycling cathode material $LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$ by leaching with a deep eutectic solvent and metal recovery with antisolvent crystallization*, Resour. Conserv. Recycl. 186, 106579.

MISHRA, S., HUNTER, T.N., PANT, K.K., HARBOTTLE, D., 2024. *Green deep eutectic solvents (DESs) for sustainable metal recovery from thermally treated PCBs: A greener alternative to conventional methods*, ChemSusChem 17(8), e202301418.

MOHAMMAD, N., FAIZAN, M., ZIA, Z., AHMAD, I., EMMAD UL HASSAN AWAN, M., ROEDAR, A., AHMAD, W., 2024. *Recovery of Cu from waste smelting slag through extraction with novel deep eutectic solvents (DESs)*, Can. Metall. Q. 1–8.

MOHAMMADPOUR, P., KARIMI, S., BEHNAJADY, B., IZADI, M., 2024. *Feasibility study of Sungun chalcopyrite concentrate electro and chemical leaching in choline chloride–urea–maleic acid deep eutectic solvent*.

MORADI, M., KARIMI, S., BEHNAJADY, B., 2024. The effect of the third component on the dissolution of chalcopyrite in deep eutectic solvents based on choline chloride and p-toluenesulfonic acid.

MORADI, M., KARIMI, S., BEHNAJADY, B., ESMAILZADEH, M., 2025. *Green solvent-driven chalcopyrite dissolution: Ternary DES (ChCl/MOA/PTSA) for high-efficiency copper extraction via RSM optimization, kinetics, and molecular dynamics insights*, Miner. Eng. 233, 109606.

MORENO, K., DÍAZ, X., ENDARA, D., SÁNCHEZ, F., ARAGÓN-TOBAR, C.F., 2024. *Zinc and lead leaching from sphalerite–galena concentrate using deep eutectic solvents based on choline chloride: Effect of roasting and iodine as oxidizing agent*, Molecules 29(16), 3742.

NASRULLAH, Z., SADDAT, M., AGYEMANG, F., LADOUCEUR, R., 2025. *Process intensification by resonant vibratory mixing for recyclable samarium–cobalt magnets after chemical leaching with deep eutectic solvents*.

NAZLI, F., HASDEMIR, I., UYSAL, E., DURSUN, H.N., GEZICI, U.O., ÖZÇELIK, D.Y., GÜRMEN, S., 2025. *Eco-Friendly Leaching of Spent Lithium-Ion Battery Black Mass Using a Ternary Deep Eutectic Solvent System Based on Choline Chloride*, Glycolic Acid, and Ascorbic Acid, Minerals 15(8), 782.

NI, S., SU, J., ZHANG, H., ZENG, Z., ZHI, H., SUN, X., 2021. *A cleaner strategy for comprehensive recovery of waste SmCo magnets based on deep eutectic solvents*, Chem. Eng. J. 412, 128602.

OKE, E.A., FEDAI, Y., POTGIETER, J.H., 2025. *Hydrometallurgical leaching of copper and cobalt from a copper–cobalt ore by aqueous choline chloride-based deep eutectic solvent solutions*, Minerals 15(8), 815.

PAIVA, A., CRAVEIRO, R., AROSO, I., MARTINS, M., REIS, R.L., DUARTE, A.R.C., 2014. *Natural Deep Eutectic Solvents–Solvents for the 21st Century*, ACS Sustainable Chem. Eng. 2(5), 1063-1071.

PAVLOUDAKIS, F., ROUMPOS, C., SPANIDIS, P.M., 2024. *Sustainable Mining and Processing of Mineral Resources. Sustainability* 16, 8393.

PEETERS, N., BINNEMANS, K., RIAÑO, S., 2020. *Solvometallurgical recovery of cobalt from lithium-ion battery cathode materials using deep-eutectic solvents*, Green Chem. 22(13), 4210–4221.

RAFATI, S., EBRAHIMI, N., SADEGHI, R., 2025. *New Family of Type V Natural Hydrophobic Deep Eutectic Solvents Based on Thymol-Acetamide/Acetanilide: Characteristics*, Intermolecular Interactions and Applications in Liquid-Liquid Extraction, Sep. Purif. Technol. 359, 130583.

RIAÑO, S., PETRANIKOVA, M., ONGHENA, B., VANDER HOOGERSTRAETE, T., BANERJEE, D., FOREMAN, M.R.S., BINNEMANS, K., 2017. *Separation of rare earths and other valuable metals from deep-eutectic solvents: A new alternative for the recycling of used NdFeB magnets*, RSC Adv. 7(51), 32100–32113.

RÜŞEN, A., ÇATAL, M.Y., TOPÇU, M.A., ALKAN, M.S., KARAKAYA, M.Ç., 2026. *Extraction of critical elements from red mud as polymetallic source by solvometallurgical method*, Miner. Eng. 236, 109946.

SALGADO, B., ENDARA, D., ARAGÓN-TOBAR, C.F., DE LA TORRE, E., ULLAURI, L., 2024. *Recovery of residual lead from automotive battery recycling slag using deep eutectic solvents*, Molecules 29(02), 394.

SARMA, S., SAHU, T.K., SHARMA, R.K., PRASUN, A., VISHWAKARMA, R., KUMAR SARMA, T., 2024. *Polyphenol Derived Natural Deep Eutectic Solvents for High Efficiency Cathode Recycling of Li-Ion Batteries*, ACS Sustainable Resour. Manage.

SHAHID, M., SAHADEVAN, S.A., RAMANI, V., SANKARASUBRAMANIAN, S., 2025. *Recommended Practices for the Electrochemical Recovery of Cobalt from Lithium Cobalt Oxide: A Case Study of the Choline Chloride: Ethylene Glycol Deep Eutectic Solvent*, ChemSusChem e202401205.

SHAHREZAEI, F., KARIMI, S., BEHNAJADY, B., 2024. *Experimental and dynamic molecular study of zinc extraction from sphalerite concentrate in ternary deep eutectic solvent*, Colloids Surf. A Physicochem. Eng. Asp. 695, 134241.

SHAKIBA, G., SANEIE, R., ABDOLLAHI, H., EBRAHIMI, E., REZAEI, A., MOHAMMADKHANI, M., 2023. *Application of deep eutectic solvents (DESs) as a green lixiviant for extraction of rare earth elements from caustic-treated monazite concentrate*, J. Environ. Chem. Eng. 11(5), 110777.

SHETGAONKAR, S.E., JOTHISH, S., DOHI, T., SINGH, F.V., 2023. *Iodine (V)-based oxidants in oxidation reactions*, Molecules 28(13), 5250.

SHIRI, H.R., MOKMELI, M., GHADAMGAHI, S.M., BABAKHANI, A., 2025. *Deep eutectic solvents (DESs) for chalcopyrite concentrate extraction: Leaching, optimization and kinetics mechanism*, J. Environ. Chem. Eng. 117779.

SHUPING, C., ZHIHAN, Z., DONG, W., WENJING, Z., TAO, Q., ZHI, W., GUOBIAO, G.L., 2025. *Selective leaching and recovery of rare earth from NdFeB waste through a superior selective and stable deep eutectic solvent*, Sep. Purif. Technol. 353, 128498.

SUDOVÁ, M., SISOL, M., KANUCHOVA, M., MARCIN, M., KURTY, J., 2024. *Environmentally friendly leaching of antimony from mining residues using deep eutectic solvents: Optimization and sustainable extraction strategies*, Processes 12(3), 555.

SUFFIA, S., DUTTA, D., 2024. Applications of Deep Eutectic Solvents in Metal Recovery from E-Wastes in a Sustainable Way, J. Mol. Liq. 394, 123738.

SVÄRD, M., MA, C., FORSBERG, K., SCHIAVI, P.G., 2024. *Addressing the Reuse of Deep Eutectic Solvents in Li-Ion Battery Recycling: Insights into Dissolution Mechanism*, Metal Recovery, Regeneration, and Decomposition, ChemSusChem 17(20), e202400410.

TANG, S., FENG, J., SU, R., ZHANG, M., GUO, M., 2022. *New bifunctional deep-eutectic solvent for in situ selective extraction of valuable metals from spent lithium batteries*, ACS Sustainable Chem. Eng. 10(26), 8423–8432.

TEIMOURI, S., POTGIETER, J.H., BILLING, C., CONRADIE, J., 2023. *The feasibility of pyrite dissolution in the deep eutectic solvent ethaline: Experimental and theoretical study*, J. Mol. Liq. 392, 123468.

TOPÇU, M.A., ÇELTEK, S.A., RÜŞEN, A., 2024. *Green leaching and predictive model for copper recovery from waste smelting slag with choline chloride-based deep eutectic solvent*, Chin. J. Chem. Eng. 75, 14–24.

TOPÇU, M.A., RÜŞEN, A., KÜÇÜK, Ö., 2021. *Treatment of copper converter slag with deep eutectic solvent as green chemical*, Waste Manag. 132, 64–73.

UNITED NATIONS, 2015. Transforming our world: the 2030 *Agenda for Sustainable Development. United Nations General Assembly Resolution* A/RES/70/1. Available at: https://docs.un.org/en/A/res/70/1

VARGHESE, A.T., MALAR, C.G., SEENUVASAN, M., JAYAPRADHA, V., 2024. *Neodymium recovery from permanent magnets: A breakthrough approach using deep eutectic solvents and mica*, J. Mol. Liq. 394, 123690.

WANG, C., AI, T., GAO, X., LU, J., LIU, J., ZHU, W., LUO, Y., 2024. *Effective recycling of critical metals from $LiCoO_2$ batteries by hydrated deep eutectic solvents: Performance, kinetic and mechanism*, J. Water Process Eng. 59, 105088.

WANG, K., HU, T., SHI, P., MIN, Y., WU, J., XU, Q., 2021. *Efficient recovery of value metals from spent lithium-ion batteries by combining deep eutectic solvents and coextraction*, ACS Sustainable Chem. Eng. 10(3), 1149–1159.

WEN, Y., HE, X., KANG, T., GU, K., DI, S., LI, L., CUI, Y., 2024. *Simultaneous separation and leaching of cathode materials from spent lithium-ion battery using ternary deep eutectic solvents*, J. Environ. Chem. Eng. 12(6), 114864.

WINARDHI, C.W., ASSUNCAO GODINHO, J.R. DA, RACHMAWATI, C., ACHIN, I.D., ITURBE, A.U., FRISCH, G., GUTZMER, J., 2022. *A particle-based approach to predict the success and selectivity of leaching processes using ethaline – Comparison of simulated and experimental results*, Hydrometallurgy 211, 105869.

XU, B., DÍEZ, N., SEVILLA, M., FERRER, M.L., GUTIÉRREZ, M.C., DEL MONTE, F., 2024. *Recycling and Reutilization of Metals Aided by Deep Eutectic Solvents: from NMC Cathodes of Spent Li-ion Batteries to Electrolytes for Supercapacitors*, ChemSusChem e202401128.

YADAV, J., SARKER, S.K., BRUCKARD, W., JEGATHEESAN, V., HAQUE, N., PRAMANIK, B.K., 2025. *Selective recovery of rare earth elements from NdFeB magnet waste via deep eutectic solvents: Process optimization and DFT insights*, Sep. Purif. Technol. 134176.

YANG, Q., LI, Y., LI, B., DUAN, P., REN, Z., ZHOU, Z., 2024. *Selective leaching and recovery of neodymium from NdFeB carbonyl residues*, Sep. Purif. Technol. 329, 125137.

YETIM, D., SVECOVA, L., LEPRÊTRE, J.C., 2024. *Lithium-Ion Battery Cathode Recycling through a Closed-Loop Process Using a Choline Chloride–Ethylene Glycol-Based Deep-Eutectic Solvent in the Presence of Acid*, ChemistryOpen 13(2), e202300061.

YU, G., NI, S., GAO, Y., MO, D., ZENG, Z., SUN, X., 2024. *Recovery of rare earth metal oxides from NdFeB magnet leachate by hydrophobic deep eutectic solvent extraction, oxalate stripping and calcination*, Hydrometallurgy 223, 106209.

YU, H., WANG, S., LI, Y., QIAO, Q., WANG, K., LI, X., 2022. *Recovery of cobalt from spent lithium-ion battery cathode materials by using choline chloride-based deep eutectic solvent*, Green Process. Synth. 11(1), 868–874.

YUAN, Z., LIU, H., YONG, W.F., SHE, Q., ESTEBAN, J., 2022. *Status and Advances of Deep Eutectic Solvents for Metal Separation and Recovery*, Green Chem. 24(5), 1895-1929.

ZHANG, J., DAO, J., WANG, J., LI, C., WANG, D., BAO, C., DONG, P., 2024. *Efficient leaching of valuable metals from NCM cathode materials by green deep eutectic solvent*, J. Clean. Prod. 438, 140636.

ZHANG, Y., RU, J., HUA, Y., CHENG, M., LU, L., WANG, D., 2025. *Priority Recovery of Lithium from Spent Lithium Iron Phosphate Batteries via H_2O-Based Deep Eutectic Solvents*, Carbon Neutralization 4(1), e186.

ZHANG, Y., WANG, B., WANG, F., DAI, Y., REN, S., HOU, Y., WU, W., 2025. *A green recyclable process for selective recovery of Li and Fe from spent lithium iron phosphate batteries by synergistic effect of deep eutectic solvent and oxygen*, Sep. Purif. Technol. 354, 128764.

ZHAO, Q., MA, S., HO, W., WANG, Y., HO, J.Y.T., SHIH, K., 2023. *Simple and environmentally friendly metal recovery from waste printed circuit boards by using deep eutectic solvents*, J. Clean. Prod. 421, 138508.

ZHENG, S., XU, S., WANG, Z., DUAN, H., CHEN, D., LONG, M., LI, Y., 2024. *Efficient leaching of valuable metals from spent lithium-ion batteries using green deep eutectic solvents: Process optimization, mechanistic analysis, and environmental impact assessment*, J. Clean. Prod. 480, 144128.

ZHOU, F., TIAN, Y., ZHANG, H., YIN, Y., WANG, Z., QIN, R., MU, T., 2024. *Enhanced Rapid and Efficient Recycling of Lithium-Ion Battery Cathode by Synergistic Effects of Ternary Deep Eutectic Solvents ChCl/MClx/Levulinic Acid*, ACS Sustainable Chem. Eng.

ZÜRNER, P., FRISCH, G., 2019. *Leaching and selective extraction of indium and tin from zinc flue dust using an oxalic acid-based deep eutectic solvent*, ACS Sustainable Chem. Eng. 7(5), 5300–5308.