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Editorial

Separation Techniques for the Efficient and Green Recovery of Metal Minerals

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1. Introduction

In 2022~2023, eight high-quality papers were published in the Special Issue of *Separations* entitled "Efficient and Green Recovery of Metal Minerals". Traditionally, the term mineral resources refers to the collection of minerals or useful elements formed through geological mineralization. With the continuous exploitation of mineral resources, the availability of rich or easily extractable minerals is progressively diminishing. People are turning to the efficient development of lean and secondary metal resources [1–4]. Our Editorial Board noticed that while the previously mentioned eight papers focus on the extraction of metals from minerals, some also investigate the reuse of metals from waste secondary resources. In this Special Issue, the efficient and green separation of Li, Co, Ni, Mn, Ti, V, and other non-ferrous metal resources is comprehensively discussed.

There are two conventional methods for separating non-ferrous metals: pyrometallurgy and hydrometallurgy. The essence of the pyrometallurgical process is the application of physical and chemical principles in chemical reactions at high temperatures, while the hydrometallurgical process consists of the large-scale application of aqueous solution chemistry or electro-chemistry. The reactions occurring in pyrometallurgical processes, including reduction, oxidation, decomposition, sulfurization, halogenation, distillation, distribution, etc., offer the advantages of fast reaction speeds, short processes, and less equipment [5]. The hydrometallurgy process usually includes three main steps, namely, leaching, purification, and sedimentation, which can efficiently separate metals from polymetallic-coexisting or lean ores [6].

In order to improve metal recovery rates, researchers occasionally employ a process combining pyrometallurgy and hydrometallurgy, such as that used in the extraction of vanadium from vanadium slag. Vanadium slag is one of the secondary resources of vanadium titanium magnetite. Vanadium slag contains valuable metals such as vanadium, titanium, iron, manganese, and chromium [7]. Individual pyrometallurgical or hydrometallurgical technologies cannot be used to separate the valuable metals mentioned above simultaneously. As the vanadium-containing phase in vanadium slag is a vanadium iron spinel structure, which has a complex lattice structure, it is difficult to efficiently extract vanadium using only the leaching process [8]. Researchers have developed sodium-roasting water-leaching and calcium-roasting acid-leaching processes for vanadium extraction. These processes consist of using NaCl or $CaCl_2$ as an additive when roasting vanadium slag at 850 °C and then leaching the roasted slag using water or H_2SO_4 [9].

The efficient and green recovery of metal minerals is a timeless topic. The efficient utilization of mineral resources is crucial for the development of modern economies and society. As traditional fossil fuels become increasingly depleted, attention is turning to solar, wind, nuclear, and hydrogen energy. However, the foundation for the development of these new energy technologies is based on the efficient utilization of mineral resources. Perovskite is a research hotspot in the field of solar energy, and the structures and properties of metal

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oxides constitute one of the main topics discussed is in this regard [10]. How to prepare pure metal oxides is an issue concerning the efficient utilization of mineral resources [11]. Large wind-power generation equipment should be equipped with high-performance wind turbines, whose performance and efficiency depend on the use of neodymium, praseodymium, and dysprosium and other rare earth elements [12–14]. Improving the distribution ratio and separation coefficients of these rare earth elements is one of the important research areas for rare earth minerals. The development of nuclear energy is based on the efficient separation of radioactive metal elements. Radioisotope separation is also an issue regarding the efficient utilization of mineral resources [15,16]. Furthermore, the safe storage and efficient preparation of hydrogen energy are closely related to the research and development of advanced metal materials. Common hydrogen storage alloys include rare earth series, zirconium series, iron titanium series, magnesium series, etc. [17–19]. These alloy elements are also extracted from mineral resources.

Whether it is the optimization of metal separation processes, the design of separation reaction equipment, or the preparation of alloy materials through metal separation, they are all popular topics in our journal. In this Special Issue of *Separations* titled "Efficient and Green Recovery of Metal Minerals", researchers discuss selective extraction processes, scale up experiments for separation processes, perform separation in rotating flow fields, and determine separation mechanisms. This Special Issue also contains a review paper concerning the separation of magnesium and lithium in salt lake brine. This Editorial aims to increase the visibility of this Special Issue and encourage scholars to publish articles about metal separation in our journal.

2. Summary of Published Articles

Lithium-ion batteries used in new energy vehicles have a lifespan of 5–8 years. With the large-scale use of new energy vehicles, waste lithium-ion batteries are attracting an increasing amount of attention [20–23]. Common types of lithium-ion batteries include ternary material batteries and lithium iron phosphate batteries. The power performance of ternary material batteries is superior, but the addition of elements such as nickel, cobalt, and manganese results in high usage costs. Waste lithium-ion batteries contain a large amount of valuable metal elements, such as Li, Co, Ni, and Mn. The traditional methods for recycling waste lithium-ion batteries mainly involve the use of sulfuric acid leaching and precipitation processes. In order to reduce the amount of waste acid polluting the environment, Kun wang et al. proposed the use of an organic acid to leach spent lithium-ion batteries. They used 2 M acetic acid, 4.0 vol.% H_2O_2, to leach spent batteries in a solid–liquid ratio of 20 g/L each at 70 °C for 40 min. The results showed that the leaching rates of lithium, cobalt, nickel, manganese, and aluminum reached 98.56%, 94.61%, 96.39%, 97.97%, and 94.7%, respectively [24]. Furthermore, due to the surge in the demand for lithium resources, researchers have further developed lithium extraction technologies using salt lake brine. Yueyu Liu presents a review of MOF nanofiltration membranes used in the separation of Li from salt lake brine [25].

In order to improve reaction efficiency, chemical production processes require the use of catalysts with good catalytic performance. However, impurities in the reaction process may react with the catalyst and precipitate its failure. Junbo Zhou proposed using roasting and leaching processes to recover Ni, Co, Mo, and V from a waste hydrodesulfurization (HDS) catalyst. The results showed that 93.9% of Ni, 100.0% of Co, 99.8% of Mo, and 92.8% of V could be recovered. Furthermore, they used recycled metal to remake $LiNi_{0.533}Co_{0.193}Mn_{0.260}V_{0.003}Fe_{0.007}Al_{0.004}O_2$ battery cathode materials, which showed excellent electrochemical performance [26].

This Special Issue includes two papers discussing the comprehensive utilization of vanadium and titanium resources. One research team proposed the incorporation of ammonium sulfate in the roasting of vanadium slag. Using FT-IR, XRD, XPS, and SEM techniques, they showed the result of the decomposition and transformation of vanadium slag during ammonium salt roasting, revealing that Fe, V, Ti, and Mn transformed into sulfate, with some of these elements presenting changes in chemical valence [27]. Titanium dioxide waste acid is a waste acid produced using the sulfuric acid method in the production of titanium dioxide [28]. Another research team discussed a new process for treating titanium dioxide waste acid. In addition to sulfuric acid, titanium dioxide waste acid contains a large amount of ferrous sulfate, which hinders the development of the titanium dioxide industry. This research team proposed using a new technique consisting of step extraction and the comprehensive utilization of titanium dioxide waste acid. They removed other impurities in the form of phosphates when iron was in a reduced state. If the iron was in the Fe(III) form, iron phosphate was formed [29].

The use of external metallurgical techniques such as microwave, ultrasound, and supergravity methods may further enhance metal extraction. Long Wang published a paper discussing the extraction of Re, Ni, Co, Al, and Cr from superalloy scraps via an ultrasonic leaching method. They found that 92.3% Re, 95.2% Ni, 98.5% Co, 98.7% Al, and 97.5% Cr could be extracted in the ultrasonic leaching process, corresponding to an about 20% improvement in the leaching rate compared to that of the conventional leaching process [30]. Chunwei Shi discussed the degradation of azo dye via ultrasound in a rotating flow field. Azo dyes are carcinogenic substances. Thus, it is necessary to explore their degradation processes. The authors found that using a combination of ultrasound and mechanical stirring led to an efficient degradation of the azo concentration in a solution without requiring the frequent supplementation of ferrous chloride solution [31].

The successful promotion of laboratory technology to industrial applications has always been a dream for researchers. The depletion of aluminum resources has led to increasing attention to the development of low-grade bauxite mines. Yang Chen extracted Al from low-grade bauxite on a semi-industrial experiment scale. Using the calcification–carbonization method for processing low-grade alumina, they found that only 0.95% Na_2O was left in the bauxite residue, while only 0.85 A/S was present in the final red mud. The total Al dissolution rate could reach over 80% [32–34].

3. Conclusions

The articles published in this Special Issue of *Separations*, titled “Efficient and Green Recovery of Metal Minerals”, cover topics ranging from the recycling of spent lithium-ion batteries and catalysts to the efficient utilization of vanadium and titanium resources, the scaling up of experiments for low-grade bauxite, and Azo degradation and rare metal extraction using ultrasound. These studies reveal that Li, Co, Ni, and Mn in spent lithium-ion batteries can be recovered via organic acid leaching processes. Mo, V, Ni, and Co in waste catalysts can be reused as synthetic cathode materials for lithium batteries. Calcification and carbonization methods can facilitate the large-scale dissolution of low-grade bauxite aluminum. Using ultrasound technologies, the efficient degradation of azo fuel and the extraction of rare metals can be achieved. Furthermore, the included review paper may provide insight into the application of MOF nanofiltration membranes to the separation of Mg and Li from salt lakes.

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