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Rhenium and Rare Dispersed Elements: Resource Base, Hydrometallurgical Extraction Pathways, and Advanced Polymer-Based Sorption Technologies

Abstract: Rhenium and some trace elements are different from other metals. Their importance comes from the fact that they are used in high-temperature alloys, optoelectronic devices, catalytic systems, and energy technologies. Because they are rare in nature and are often found in small amounts in copper, molybdenum, zinc, and aluminum ores, it is hard to extract them. This depends on how the metallurgical industry works and how much money it makes. This, along with the fact that the quality of the ore is getting worse, has brought to light a wider range of raw materials, such as off-gases, metallurgical dust, coal waste, and spent catalysts. Hydrometallurgical methods are the main ways to extract minerals. They include different combinations of leaching, ion exchange, solvent extraction, and sorption. Polymeric materials, particularly interpolymer hydrogel systems made of polymethacrylic acid and poly-4-vinylpyridine, have become useful for binding perrhenates and trivalent lanthanide ions in the last few years. This is because the interactions between the polymers are controlled and work together in the polymer matrix. These improvements make it possible to extract a wider range of raw materials and open up new ways to selectively extract metals at very low concentrations. This review summarizes information about the geological and anthropogenic resource base, the most common ways to get rhenium and trace elements, and the latest technological advances in processing these materials.

Keywords: rhenium; rare elements; hydrometallurgical extraction; technogenic raw materials; sorption; interpolymer hydrogel systems; ion exchangers; poly (methacrylic acid); poly (4-vinylpyridine); polymer–polymer complexes; sorbent materials; critical metals; resource recovery; microwave-assisted leaching.

Introduction

Rhenium, along with the metals categorized as "rare dispersed" elements — gallium, germanium, indium, selenium, tellurium, and thallium — comprises a set of resources valued primarily for their particular technological uses rather than the quantity of their extraction. They don't usually form distinct mineral assemblages as other non-ferrous metals do. Instead, they are found in small amounts spread out throughout the lattices of sulfides, silicates, oxides, and substances made from coal. The processing of copper, molybdenum, zinc, and aluminum is mostly what makes them available. This means that changes in the production of these main metals have a direct effect on the stability of supply chains (European Commission, 2023).

Rhenium is the one that is most limited in terms of where it can be found and how it can be used. It is mostly found in molybdenite, where it replaces molybdenum in a very small amount, with an average crustal abundance of about one part per billion. Thus, the roasting of molybdenum concentrates, and, in some cases, catalytic processes are closely related to industrial recovery. High levels of rhenium have been found in different porphyry copper-molybdenum systems, such as deposits in Chile, the United States, Kazakhstan, and Armenia (Werner et al., 2023; Wang et al, 2021). The stability of the perrhenate ion (ReO_4^-) in different oxidizing environments is an important reason why hydrometallurgical methods are so popular in modern industry.

The conditions for other distributed elements are just as complicated. Gallium is often extracted from bauxite liquors, germanium from sphalerite or coal-related substances, and selenium and tellurium from anode slimes produced during copper electrorefining. They have many uses, such as supporting III–V semiconductor technologies, broadband optical fibers, transparent conductive coatings, and thermoelectric modules (European Commission, 2023). The production of renewable energy systems and modern electronics is not keeping up with the rising demand for them.

A lot of problems that won't go away are making it hard for them to get better. This includes very small amounts in most feedstocks, chemical affinity for main elements that limits selectivity, and the instability of certain oxidation states, especially in phases that contain germanium and tellurium. As a result, industrial wastes like smelter dust, used catalysts, coal fly ash, and zinc production recycling liquors have become interesting as possible feedstocks that can be used to make primary ores (Joo & Kinas, 2012; Arroyo et al, 2009; Haghighi et al., 2018; Kim et al., 2015).

Hydrometallurgical methods are still the most important part of modern processing systems. Gallium and germanium are often leached under conditions of chloride or fluoride; indium needs a very precise pH range; and rhenium in the form of ReO_4^- is best for ion-exchange and sorption techniques. New technologies like ionic solutions, membrane separation, and microwave activation have made it easier to work with complicated or low-quality materials (Prusty et al., 2021).

Mineralogical position and global distribution of rhenium and trace elements

Rhenium and trace elements have a very uneven distribution, which is what makes them different from most metals. Rhenium is mostly found in molybdenite, where it can be found in amounts of hundreds of grams per ton. In most copper-molybdenum porphyry deposits, the amount of rhenium in molybdenite ranges from 0.5 to 30 g/t, and in bulk ore, it is less than 1 g/t. Because of this low abundance, there aren't many deposits that can be thought of as economically important. Gallium and germanium have similar problems. They are usually found in bauxite, sphalerite, and coal deposits, but they don't often form their own mineral formations. Because these elements are spread out, they need to be processed in a way that combines recovery with the production of major industrial metals. For instance, gallium is taken from bauxite during Bayer processing, germanium is taken from zinc sulfide concentrates and coal fly ash, and tellurium is taken from anode slimes during copper electrorefining. Because of this interdependence, the supply of dispersed elements is at risk of changes in base metal production and the limits of current refinery processes.

Secondary and technogenic materials as an emerging resource base

The decline in ore grades and the growing difficulty of mining operations have made people more interested in secondary technogenic sources. Metallurgical off-gases, dusts, sludges, spent catalysts, and waste materials from the copper, molybdenum, and zinc industries often have dispersed elements in higher amounts than natural ores. For example, the amount of rhenium in flue dusts or roaster gases can be hundreds of parts per million (ppm), which makes secondary extraction possible. Spent platinum–rhenium catalysts from the petrochemical industry are some of the best secondary sources because they can contain up to several percent rhenium.

Processing technogenic materials has a number of benefits. For example, the material is often already in a fine-grained or oxidized state, which makes leaching easier. Also, there is less waste, which is good for the environment, and the overall energy footprint is lower than mining virgin ores. As demand around the world grows, secondary resources are likely to become a big part of the supply chain for rhenium and dispersed elements.

Hydrometallurgical pathways for the recovery of rhenium and dispersed elements

Hydrometallurgy is the main way to get rhenium and other trace elements back because the ionic states in solution make it possible to control dissolution and separation very precisely. The speciation of these metals under different redox conditions affects the effectiveness of leaching regimes and the planning of future purification processes.

Acidic leaching is still widely used for germanium, gallium, and indium because solutions based on chloride and sulfate make it easier to make soluble compounds. Acidic conditions make it easier to extract rhenium, especially when the element is in oxidized residues, which helps it dissolve (Mahmoudi et al., 2021).

Alkaline leaching works better for metals that are amphoteric or have stable anionic forms, like gallium and tellurium. These situations often improve selectivity by stopping other drugs from working.

Oxidative leaching is very important for getting rhenium out of the ground. Strong oxidizing agents like nitric acid, hydrogen peroxide, or the oxidizing environment created during roasting help change rhenium compounds into perrhenate ion, which is important for the next steps in the separation process.

New technologies and advanced methods for extraction processes

• Ion exchange methods work well for ReO_4^-. These allow for selective extraction using anion exchange resins or specially designed polymer sorbents, as well as solvent extraction for indium, gallium, and Germanium using organophosphorus extractants (Redlinger et al., 2015).

• Ways to make GeO_2 by precipitation;

• Sorption on functionalized polymers with a strong attraction to perrhenate and similar oxyanions;

• Membrane and electrochemical methods are useful because they can lower energy costs and make processes work better together.

New ways of extracting things and new technologies for extraction methods

Over the past ten years, there has been a shift toward more environmentally friendly extraction methods that make it easier to work with more complex feedstocks. Many areas of technology need special attention:

- Ionic liquids and deep eutectic solvents provide controlled solvation conditions and reduced volatility;
- Microwave-assisted leaching is used to speed up dissolution and change how different phases interact;
- Bioleaching of germanium and gallium from coal and zinc processing waste, aided by microbial activity that increases metal mobility;
- Nanostructured sorbents, hybrid polymer-inorganic composites, and novel ion-exchange systems; Employed a combination of hydrometallurgical processes to enhance selectivity and reduce waste.

All of these methods are different from pyrometallurgical methods, which use a lot of power. They are also adaptable and can process various feedstocks at low temperatures.

Interpolymer hydrogel systems and remotely activated ion exchangers are two of the most active areas of research right now. Compared to regular resins, they offer a completely new way to choose. Polymethacrylic acid (PMAA) and poly-4-vinylpyridine (P4VP) are two types of polymer networks that work together in a controlled way to make these materials. When you touch or activate the hydrogels from a distance, they change shape a lot. This rearrangement changes the density and accessibility of ionogenic groups, how the material swells, and creates a microenvironment that makes it easier for oxyanions and multivalent cations to bind. Jumadilov and his team found that systems based on PMAA/P4VP absorb cerium, europium, scandium, and lanthanum better. The polymers interact at the polymer-polymer interface (Jumadilov et al., 2022; Jumadilov & Imangazy, 2023; Suleimenova et al., 2025). Interpolymer systems may demonstrate an atypically high affinity for yttrium, a phenomenon termed "anomalous" sorption, linked to alterations in the internal structure of the polymer network (Jumadilov et al., 2023; Dyussembayeva et al., 2024). Interpolymer systems, such as polyacrylic acid and poly-4-vinylpyridine, exhibit significant potential for rhenium extraction due to their enhanced selectivity for the perrhenate ion (ReO_4^-) in the presence of other anions, a frequent occurrence in industrial solutions (Jumadilov et al, 2024).

These results show that interpolymer systems are a type of sorbent that can be easily changed and is flexible. They can change the chemical environment at the molecular level, which lets them get rhenium and rare elements from both primary and secondary sources in dilute and complex media. Adding them to commercial hydrometallurgical flowsheets in the future will make extraction more efficient and promote more eco-friendly methods.

Proposed new section: results from recent experimental studies

In addition to the broader developments outlined above, recent experimental investigations have provided new insights into the selective extraction of rhenium and dispersed elements from complex, low-grade solutions (Baishibekov et al., 2025). This study aimed to see how well interpolymer hydrogel systems and remotely operated ion exchangers worked in settings that were similar to technogenic process streams. Special attention in recent studies has been given to solutions containing competing oxyanions and multivalent cations, as such species often reduce the selectivity of conventional sorbents. Experimental observations demonstrate that modifications to microenvironmental polarity and swelling characteristics of poly (methacrylic acid): poly (4-vinylpyridine) interpolymer networks can significantly affect their ion-binding interactions. Researchers found that this tunability changed both the ability to absorb ions and the order in which they bind when there were several trace components present at the same time. Enhanced stabilization of perrhenate within the tailored interpolymer matrix resulted in consistently higher distribution coefficients compared with conventional anion-exchange resins. Comparable behavior was observed for lanthanide and yttrium ions, suggesting that the underlying mechanisms are linked to cooperative conformational adjustments within the polymer network.

These findings represent an early stage in the development of such materials but highlight their potential as adaptable platforms for metal-ion separation. Their capacity to function effectively in the presence of diverse impurity ions is particularly relevant for industrial environments, where feed compositions fluctuate, and target metals are often present at trace levels.

Conclusion

As technology-driven industries continue to expand, the strategic importance of rhenium and dispersed trace elements becomes increasingly evident. Their distinctive chemical and physical characteristics support a wide range of applications, including high-temperature superalloys, catalytic systems, optoelectronic components, and renewable-energy technologies. Despite this significance, the extraction of these metals remains challenging due to their low natural abundances, dispersed mineralogical occurrences, and dependence on by-product recovery from major base-metal operations.

Recent advances point to a gradual shift toward hydrometallurgical methods that prioritize selectivity and reduce environmental impact. Progress in solvent extraction, solid-phase sorption, ionic-liquid systems, and alternative leaching strategies has broadened the possibilities for treating primary ores as well as secondary, technogenic materials. The diversification of resource bases through the use of recycled and industrial residues is becoming increasingly important as global demand continues to rise.

Sustained development of integrated and adaptable recovery processes will be essential to ensuring the long-term availability of rhenium and dispersed trace elements in a rapidly evolving technological landscape.

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