

Editorial

Editorial for the Special Issue: “Valuable Metals Recovery by Mineral Processing and Hydrometallurgy”

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Achieving the sustainable development of our society and facilitating breakthrough innovations necessitates metals. All metals (not only those classified as precious and critical or strategic for the present and near future), required both for advanced technologies and our everyday life, are valuable, and their demand will increase with time.

Humankind has been driven to use more efficient and complex techniques for processing ores, which requires novel approaches and technologies for mineral processing and the extraction of metals.

In order to obtain enough metals for future development, the recovery of metals from secondary sources, such as solid and liquid waste from mining, mineral processing, and extractive metallurgy, has to be considered.

Potential challenges to future metal extraction technologies also include soaring energy prices, the necessity to secure safe and clean water, and the need to use resources efficiently and comprehensively, while protecting the environment.

The solutions to all the aforementioned problems require new theoretical backgrounds and technical developments, including reagents and operational innovations of processes and technologies, when the problems associated with both primary ores and secondary technogenic resources are tackled.

Papers discussing all the above mentioned aspects and challenges and presenting solutions to metal recovery through mineral processing and hydrometallurgy are gathered in this Special Issue.

All metals, after being mined, are processed through a mineral beneficiation stage, followed by metallurgy/hydrometallurgy, or sometimes enter directly to hydrometallurgy.

The flotation concentration of metal-bearing ores is probably the most widely used mineral beneficiation process. Its efficiency depends on the minerals' preparation, i.e., grinding, flotation reagent types and concentrations, and other parameters of the flotation process, such as pulp pH values, oxidation–reduction conditions, temperature, applied external energy impacts, etc.

The first part of this collection is devoted to flotation.

The effects of different grinding media (mild steel, MS, and stainless steel, SS) and milling conditions (wet or dry, the latter with a potential to decrease the freshwater use) on the results from copper pyrite (Cu-Py) flotation are studied [1]. Galvanic interaction between sulphide minerals and the grinding media is eliminated by dry grinding. This results in higher redox potential, irrespective of type of milling media compared to wet grinding, thus leading to a high flotation rate of Cu and obtaining Cu concentrate with a higher grade, especially when SS is used. However, in this case, the Cu recovery is lower due to the instability of the froth structure and the coalescence of air bubbles in flotation. Flotation froth is the most stable structure in the case where MS balls are used in milling. The highest separation efficiency, and hence, the best flotation performance, is achieved under wet grinding conditions with MS balls.



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Furthermore, studies on the dependence of the technological results of non-ferrous sulfide ores (copper–arsenic-bearing and non-bearing arsenic, lead–zinc, and polymetallic) flotation on the pulp oxidation–reduction potential (presented with respect to the standard hydrogen electrode, SHE, i.e., Eh) are reviewed [2]. Findings on the relation of Eh and collector-less flotation are presented. Changes in the pulp potential due to different gases application and various reagents addition are considered. The influence of the grinding medium on the pulp Eh, and hence, on the flotation results, is presented through various examples. The relation between the oxidation–reduction potential and reagent effects is exhibited and explained. pH–Eh ranges of different minerals' flotation, as recorded in various studies, are summarized and visualized jointly for all mentioned ores. It is concluded that the pulp Eh and pH values govern the reactions occurring between the various minerals in the pulp and collectors, and thus, the flotation results. It is proposed to use jointly pulp Eh and pH values and the pH–Eh diagrams (that include the main species of the elements forming the minerals in a given flotation pulp and the main reagent species) to control flotation process.

As mentioned, use of the most suitable flotation reagents is decisive for the overall process results. This is especially important when it comes to critical high-tech and strategic metals such as molybdenum (Mo), rhenium (Re), and Cu. It is known that 25% to 30% of these metals end up in rough flotation tailings when conventional reagents are used. A new reagent—dithiopyrylmethane (DTM) composite—is proposed [3]. It forms a complex DTM–Re compound and chemically adsorbs on rhenium-containing molybdenite, ensuring an increase in Re recovery into the bulk Cu–Mo–Re concentrate by 17%, reducing the loss of Re with flotation tailings twofold, and subsequently providing 97.6% Re extraction from molybdenum concentrate by autoclave leaching.

Finally, in this part of the Special Issue, the results of theoretical and experimental studies are presented on (i) the substantiation and development of criteria that characterize the efficiency of overcoming the energy barrier of internal cohesion forces during the grinding of complex ores; and (ii) the substantiation of comprehensive criteria for assessing the effectiveness of physical and energy impacts during ore beneficiation and a complex criterion that can be used for the intensification of the entire mineral beneficiation process [4].

Hydrometallurgical technologies are a powerful means of extracting metals both from concentrates and directly from poor copper ores and ores containing precious metals or rare earth elements (REEs). The second part of this Special Issue is devoted to hydrometallurgical methods.

Bioleaching is an environmentally friendly technique that uses microorganisms to remove metals from ore in cases when the traditional extraction methods (most often applying strong acids or alkaline solutions) are not economically viable. In addition to the most well-known and widely used microorganisms, new ones are being explored. A new strain of *Leptospirillum* sp., namely, *L. ferrodiazotrophum* Ksh-L, was isolated from a dump-bioleaching system of the Kashen copper–molybdenum mine and studied for its ability to leach Cu and iron (Fe) from ore [5]. Ksh-L can efficiently oxidize chalcopyrite, thus mobilizing Cu and Fe in leachate. When *L. ferrodiazotrophum* Ksh-L is used in association with *At. thiooxidans* ATCC 19377, the leaching efficiency is nearly doubled. It is proposed to use this association to enhance the efficiency of copper extraction from chalcopyrite.

Gold (Au) recovery from refractory ores is a long-standing problem that still attracts scientists' attention. Guner et al. demonstrated that diagnostic leaching, in combination with automated mineralogy, can be used as a fast and practical method to examine the processability of run-of-mine ore and flotation concentrate [6]. Diagnostic leaching provides direct indicators of the material's processability, while the automated mineralogy gives very detailed information about the gold deportment and minerals that are present in the gangue and can affect the further processing of Au-bearing concentrate. Based on the findings of the proposed combination of methods for mineral study, the consecutive steps are proposed for the material treatment and Au recovery.

Most gold deposits are associated with sulphides such as pyrite and arsenopyrite. When the minerals exhibit refractory properties due to Au occlusion in the minerals' matrix, conventional cyanidation usually extracts less than 50% of the Au that is present in ores. In such cases, simultaneous pressure oxidation and cyanidation is often applied in order to dissolve the precious metal. The effectiveness of this extraction process is influenced by the cyanide (NaCN) concentration, oxygen pressure, and temperature. Optimal ranges of those leaching conditions have been proposed by Soto-Urbe et al. [7].

Carlin-type gold ore is typical refractory ore where gold ore grains are finely distributed and present as invisible or submicroscopic gold, encapsulated in arsenopyrite and pyrite. The leaching of these ores is difficult because the fine gold is wrapped in pyrite and arsenopyrite. The oxidation roasting pre-treatment technique is proposed to treat such gold ore [8]. A two-stage roasting process is proposed: in the first stage, arsenic is removed; in the second stage, sulfur is removed. The roasting almost completely oxidizes pyrite and arsenopyrite to hematite. The share of exposed gold and oxide-encapsulated gold in the ore increases considerably (over 88% of the total Au) and the share of sulfide-encapsulated gold is reduced almost to 0%. Exposed Au and the Au encapsulated in the hematite porous structure is easily leached by cyanide solution, ensuring total Au extraction of over 83% from this ore type.

Further study revealed the oxidation and dissolution behavior of pyrite in an alkaline environment, with the aim of facilitating Au exposure in the subsequent leaching [9]. The conclusion from the applied electrochemical testing techniques (cyclic voltammetry, linear scanning voltammetry, current–time, and electrochemical impedance spectroscopy), complemented with analytical methods such as XPS and SEM–EDS, is that the oxidative dissolution of pyrite occurs preferably in an alkaline environment with a pH of around 12, and an oxidation potential above 0.9 V (vs. SHE). As a result of pyrite oxidation, stable species (polysulfides, S_x^{2-} , and thiosulfates, $S_2O_3^{2-}$) are generated, which possess oxidizing and coordinating abilities in the alkaline system. The idea has been posited to leach gold by making full use of the sulfur in gold-bearing sulfide minerals.

Hydrometallurgy is also used in obtaining other metals. One possibility is intensifying the leaching process through the preliminary energy impact (a combination of thermal, electrochemical, and ultrasonic treatment) to ensure the intensive breakdown of mineral complexes and grains in eudialyte concentrate, with the aim of enhancing zirconium (Zr) and REE recovery [10]. The proposed treatment ensures 87.0–91.7% recovery of Zr and 76.0–81.1% recovery of REE in the pregnant leach solution (PLS). A process for the selective recovery of Zr and REEs from the PLS of eudialyte concentrate is proposed, based on a combination of chemical precipitation, sorption, and elution methods.

Currently, when rich ore deposits are practically exhausted all over the world and the development of depleted and/or complex ores is required, more and more attention is being paid to extraction from old mining operations and metallurgical waste, which are often richer sources of metals than currently developed deposits. Another unconventional source of metals is liquid waste from mining, mineral processing, and extractive metallurgy. The third part of this Special Issue is dedicated to metal extraction from solid and liquid mining waste.

For example, Kiprono et al. pointed out that a considerable degree of mining and mineral processing tailings that hold strategic metals are available in Kenya [11]. Modern flotation and hydrometallurgical methods are outlined as an important solution to efficiently extract strategic and critical metals from these secondary sources while reducing environmental effects.

Brown corundum dust is a solid waste generated during the preparation of brown corundum using bauxite as raw material. The dust has a relatively high gallium (Ga) content. However, Ga cannot be leached with satisfactory recovery through the application of conventional water and/or acid leaching. The reason is that Ga is dispersed in the potassium-rich phase, wrapped by amorphous silicate and the corundum phase. A process route involving roasting activation (with sodium carbonate) and sulfuric acid (H_2SO_4)

leaching is proposed to extract Ga from brown corundum dust [12]. Due to roasting, the corundum and amorphous silicate are transformed into sodium silicate and aluminosilicate salts that enable Ga to pass to the pregnant leach solution when H_2SO_4 leaching is applied.

Boiler ash is a solid waste formed by the combustion of heavy fuel oil in power plants. It contains valuable metals, such as vanadium, nickel (Ni), zinc (Zn), iron (Fe), and magnesium (Mg). Salt roasting and water/acid leaching of boiler ash are conventional approaches to extract high-purity vanadium and concentrates of other metals in the residue. Hydrometallurgical processing of the water leaching solid residue aiming for the high-purity and cost-effective extraction of valuable metals such as Ni, Zn, Fe, and Mg is proposed [13]. It is based on H_2SO_4 leaching at elevated temperature. After Fe and Mg removal as $\text{Fe}(\text{OH})_3$ and $\text{MgC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$, high-purity nickel and zinc hydroxides are precipitated, which are transformed to the corresponding pure oxides by calcination.

Valuable metals can be recovered from wastewater from mining, metallurgy, and other industries through their adsorption on natural zeolites as safe and abundant materials. Tsitsishvili et al. [14] identified the ability of Georgian heulandite, treated with dilute hydrochloric acid solutions, to uptake relatively high amounts of silver, copper, and zinc.

Overall, the papers gathered in this Special Issue show that valuable metals can be recovered from difficult-to-process or impoverished ores, as well as from nontraditional sources by applying up-to-date beneficiation methods and hydrometallurgical approaches, based on a solid theoretical background, supported by modern analytical methods and software modeling.

Conflicts of Interest: The author declares no conflicts of interest.

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