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Editorial

Advanced Technologies in Bio/Hydrometallurgy for Recovery and Recycling of Metals

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1. Introduction and Scope

Studying innovative and sustainable technologies for the recovery and reuse of raw materials (RMs) from primary and secondary resources is fundamental for economic and industrial development in compliance with environmental protection and in the context of a circular economy.

Bio/Hydrometallurgy consists of leaching and recovery unit operations. Leaching is the solubilization of metals from a solid phase using chemicals or biological agents, whereas recovery is the extraction of metals from polymetallic leachate using physicochemical processes, electrowinning, or biological processes.

Bio-hydrometallurgical processes are new solutions offering environmentally sustainable practices in the mining and environmental sectors for the extraction of base, precious, and toxic metals and rare earth elements (REE) and for the valorization of secondary resources rich in critical raw materials (CRMs), which are fundamental in modern technological applications.

The economic concerns of these processes, which are closely linked to the choice and optimization of the experimental parameters, are of great importance.

The articles included in this Special Issue contribute to the improvement of innovative bio- and/or hydrometallurgical processes applied for the recovery of valuable and critical metals.

I would like to thank the authors who accepted this invitation, which has helped us to produce a high-impact, high-quality Special Issue on "Advanced Technologies in Bio/Hydrometallurgy for Recovery and Recycling of Metals".

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2. Contributions

Researchers around the globe investigating advanced bio/hydrometallurgical technologies for the recovery and recycling of metals have been invited to submit research papers, thereby allowing readers to recognize the common points between the different technologies. Among the submitted manuscripts, twelve articles have been published in this Special Issue.

The papers are all of high scientific value, and the experimental activities carried out fall into various disciplinary sectors, thus confirming the importance of the study of the titular topic in different scientific and technological fields. An overview of the published papers is given below.

The results concerning the leaching of metals from computer PCBs via electrochemical hydrochlorination using alternating current (AC) with an industrial frequency (50 Hz) have been presented in [1]. Leaching was carried out with a disintegrator-crushed computer motherboard and mixed computer PCBs with a particle size (d) of <90 μm. The leaching efficiency of metals including Fe, Sn, Mn, Al, Cu, Zn, Pb, Ni, Ti, Sb, Cr, Co, and V was evaluated with respect to certain process parameters, such as AC density, experiment duration, hydrochloric acid concentration in the electrolyte solution, solid/liquid ratio, electrolyte temperature, and the loading option for the raw material.

The research results showed that AC superimposition significantly intensifies the leaching of metals.

An innovative cryo-mechano-hydrometallurgical process (named LIBAT) was demonstrated on a pilot scale for the treatment of EOL lithium primary batteries with Li(0)-MnO_2 chemical properties [2]. The process enabled the recycling of steel scraps from external cases after cryomechanical dismantling and the recovery of Mn and Li products after hydrometallurgical processing. The environmental impacts and the economic sustainability of the process were evaluated and compared with an innovative pyrometallurgical approach allowing for Li recovery, confirming the benefits of the proposed process due to a reduction in energy consumption.

The extraction and recovery of metals from spent hydrodesulfurization catalysts have been studied, for which lab- and pilot-scale results were achieved in the overall process [3]. These catalysts contain valuable metals such as cobalt (Co), molybdenum (Mo), nickel (Ni), and vanadium (V). The total recovery yields were nearly 61% for Mo and 68% for V, which were much higher compared with their initial concentrations in the spent Co-Mo catalysts.

The effect of varying process parameters during the bio-catalyzed leaching of metals from end-of-life printed circuit boards (PCBs) was investigated in [4]. Fragmented PCBs were subjected to indirect bioleaching in a stirred tank reactor while pulp density, pH, and initial ferric iron content were varied. An iron-oxidizing *Acidithiobacillus ferrooxidans* 61 microbial strain was used to generate the lixiviant through oxidizing Fe(II) to Fe(III). The achieved results offer possibilities for further studies at higher pulp densities that would advance the bioleaching approach such that it facilitates economical and environmentally friendly technology for the urban mining of non-ferrous metals.

A new scheme for leaching metals from computer-printed circuit boards (PCBs) pre-crushed in a disintegrator has been proposed in [5]. The processes of chlorine production and hydrochlorination are implemented in one reactor under the action of an alternating current (AC) at an industrial frequency (50 Hz). This technology for recycling electronic waste (e-waste) demonstrates high economic efficiency and remarkable environmental safety.

A mycorrhizal-assisted phyto-mining (MAP) system composed of *Helianthus annuus*, the arbuscular mycorrhizal fungus *Rhizophagus intraradices*, and Zn-rich volcanic ashes was applied in bioreactors for the recovery of CRMs (Sr and P) and SRMs (Cr, Zn, Cu, Mn, Rb, and Ni) from mining wastes of the Los Cóndores mine (Argentina) [6]. It proved to be a promising and cost-effective biotechnology applicable in agronomical practices, and the recovery of CRMs and SRMs from plant biomass via hydrometallurgy was demonstrated.

Cyanobacteria *Arthrospira platensis* was employed for Y(III) recovery from contaminated wastewater through biosorption and bioaccumulation processes [7]. Yttrium is an element of critical importance for industry and technology. Experiments performed using *Arthrospira platensis* showed a great potential for application in the recovery of rare earth elements from wastewater.

In one study, bioleaching was proposed as a method for the removal of nickel from bulk copper–nickel sulfide concentrate and the acquisition of a concentrate containing copper as a chalcopyrite [8]. This approach is based on the variable refractoriness of sulfide minerals in ferric sulfate solutions and oxidation by acidophilic microorganisms. It was demonstrated that the bio-beneficiation of bulk sulfide concentrates is a promising field of biohydrometallurgy, which may be highly attractive for the improvement of commercial applications.

The authors of [9] studied the leaching of zinc for its recovery from electric arc furnace dust with sulfuric acid solutions at an ambient temperature and atmospheric pressure along with the reuse of the leaching process residue as a raw material for ceramic materials. This research developed a new form of environmental hydrometallurgy in which metallic elements of interest are valorized and the production of waste is avoided, thereby reducing the deposition of hazardous waste in landfills and the extraction of raw materials for the manufacture of construction materials.

One study evaluated the feasibility of obtaining recoverable copper from different waste dumps in the mining district of Linares (Spain) using hydrometallurgical techniques [10]. A significant percentage of copper was extracted from the waste dumps, demonstrating that the waste, after its processing, can be used in bituminous mixtures, rendering it a product of a closed cycle of materials in which no waste is produced.

Mycorrhizal-assisted phytoextraction (MAP; *Helianthus annuus*–arbuscular mycorrhizal fungus *Rhizophagus intraradices*–Zn-volcanic ashes) was employed for the recovery of secondary and critical raw materials (SRMs and CRMs, respectively) from Joda West (Odisha, India) mine residues according to a novel multidisciplinary management strategy [11]. The final recovery of SRMs and CRMs obtained via hydrometallurgical techniques, with final purification via selective electrodeposition, proved the viability and cost-effectiveness of this approach. The results are promising for MAP application on a larger scale, constituting an effective circular-economy-based approach.

The pressure-based hydrothermal oxidation of arsenic (III) ions in a H_3AsO_3-Fe^{2+}-Cu^{2+}-H_2SO_4 system formed during the processing of arsenic-containing sulfide non-ferrous metals was studied in [12]. This research is relevant because the low-grade polymetallic materials, such as copper–zinc and copper–lead–zinc, and poor arsenic-containing copper concentrates obtained using hydrometallurgical methods are becoming increasingly important due to the depletion of rich and easily extractable mineral resources and the need to reduce harmful emissions from metallurgy, especially given the high content of arsenic in ores.

3. Conclusions and Outlook

A variety of topics comprise this Special Issue presenting recent developments in advanced bio/hydrometallurgical technologies for the recovery and recycling of metals.

As Guest Editor, I am very pleased with the success of the issue, the final result, and the quality and originality of the contributions, and I hope that the published articles in this Special Issue contribute to the advancement and future development of research in this field.

I would like to warmly thank all the authors for their contributions and all the reviewers for their efforts in ensuring a high-quality publication. Sincere thanks are also due to the Editors of *Metals* for their continuous support and to the *Metals* Editorial Assistants for their valuable and inexhaustible engagement and support during the preparation of this Special Issue. In particular, I offer my sincere thanks to Mr. Toliver Guo, Assistant Editor, for his help and support during the publication of this Special Issue.

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