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Editorial

Advanced Sorbents for Separation of Metal Ions

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1. Introduction and Scope

Effective, sustainable, and selective methods for recovering or removing metals from various media, such as mining leachates, recycling waste, industrial effluents, and natural water, are necessary due to the increasing demand for metals and stringent environmental constraints [1,2]. Separation of metal ions is an essential stage in recovery and removal procedures [3,4].

Adsorption is considered an effective separation technique that offers excellent workability in process operation and design, and the sorbent can be reused after proper regeneration [5,6]. Adsorption methods for separating metal ions based on traditional sorbents (inorganic clays/zeolites, activated carbon, and polymeric resins) face limitations in terms of selectivity, efficiency, and cost-effectiveness [7].

Recently, advanced sorbents made from new and modified materials, including modified natural minerals [8,9], modified carbons/biochar [10,11], agricultural waste and biosorbent [12,13], metal–organic frameworks (MOFs) [14], synthetic polymers [15], magnetic sorbents [16,17], hydrogels [18], and nanosorbents [19], are promising alternatives for overcoming these challenges. These sorbents have a high surface area, tunable pore structures, and functionalized surfaces, which improve their metal-ion adsorption capacity, selectivity, and kinetics [20]. Various methodologies, including surface modification, hybridization, and template-assisted synthesis, have been employed to develop advanced sorbents [21]. The sorbents with incorporated functional groups, chelating agents, or ion-imprinted polymers may exhibit improved affinity and selectivity toward specific metal ions [22].

Metal-ion adsorption using advanced sorbents is significant in various fields. These sorbents are particularly valuable in water treatment processes, where they are used to remove heavy metals from industrial wastewater [23]. In hydrometallurgy, advanced sorbents are essential in the recovery and purification of valuable metals, such as noble metals [24] and rare earth elements [25], from leachates and process streams in mining and metallurgical operations. Furthermore, the separation of actinides from radioactive waste streams [26] has benefited from radiation-resistant sorbents [27]. Environmental remediation also relies on sorbents to remove metal ions from soil [28] and groundwater [29]. In analytical chemistry, dispersive solid-phase microextraction (DSPME) is a promising technique for the preconcentration and clean-up of trace metal ions in complex matrices [30]. The choice of sorbent in these applications depends on several factors: the metal ions of interest, the composition of the aqueous matrix, and the adsorption characteristics (capacity, selectivity, and reusability) [20].

To optimize metal-ion separation performances, it is essential to understand how the physicochemical properties of both the sorbent and the metal ions influence the adsorption mechanisms. The surface complexation model involves the formation of complexes between the functional groups on the sorbent surface and the metal ions driven by electrostatic interactions, ion exchange, and chelation [31]. Other key processes are precipitation and co-precipitation, where metal hydroxides or other insoluble metal compounds form on the sorbent surface or within its porous structure [32]. Reduction and redox reactions can also

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occur, with the sorbent surface catalyzing the reduction of metal ions to their zero-valent or lower oxidation states [33]. Electrostatic interactions, which depend on the solution pH and the point of zero charge of the sorbent, result in either attraction or repulsion between the sorbent surface and metal ions [34]. Additionally, pore and intraparticle diffusion are critical for governing the transport of metal ions within the porous sorbent structure, thereby affecting the adsorption kinetics and isotherms [35,36]. In general, understanding these mechanisms is crucial for the design and optimization of sorbents and for the development of predictive adsorption models.

This Special Issue on “Advanced Sorbents for Separation of Metal Ions” in *Metals* brings together up-to-date research that addresses metal-ion separation challenges through innovative sorbent materials and methodologies. A variety of advanced sorbents, including polymeric materials, silica adsorbents, ion exchange resins, and biosorbents, were investigated.

2. Contributions

The contributed articles in this issue explore novel or modified sorbents based on wood ash, bone char, resins, silica, brown seaweed, eggshells, graphene, ionic liquids, and methacrylate polymers, and discuss the adsorption processes in which these sorbents were used.

Liu et al. presented novel silica-based adsorbents impregnated with crown ethers that demonstrate high selectivity for strontium (Sr) ions in concentrated nitric acid solutions. These adsorbents exhibit improved stability and reduced organic leakage, addressing the significant limitation of crown ethers in acidic environments. This study introduced new materials and provided insights into the adsorption mechanisms, paving the way for their application in nuclear waste management.

Smičiklas et al. evaluated the use of wood ash and bone char for manganese (Mn) removal from acid mine drainage (AMD). Their research revealed that wood ash is highly effective due to its neutralization capacity, whereas bone char shows rapid and efficient Mn separation with minimal interference from other ions. This study emphasizes the potential of using waste materials in sustainable AMD treatment processes.

Hansen et al. investigated copper (Cu) biosorption using brown seaweed. Their work identified optimal conditions for maximum copper uptake and efficient biosorbent regeneration, highlighting the potential of seaweed as a cost-effective and environmentally friendly sorbent for copper removal from wastewater.

Marković et al. explored the use of raw eggshells in copper ion biosorption. This study analyzed the process parameters, equilibrium, kinetics, and thermodynamics, demonstrating that eggshells are effective, low-cost adsorbents for copper removal. The research also optimizes the biosorption process using Response Surface Methodology (RSM).

Mikeli et al. focused on the recovery of scandium (Sc) from titanium industry waste using ion-exchange resins. Their findings indicate that certain resins are highly efficient in extracting scandium without significantly affecting the chloride solution, making this process feasible for industrial applications.

Slavković-Beškoski et al. introduced a novel dispersive solid-phase microextraction method using a poly(HDDA)/graphene sorbent for rare earth element (REE) analysis in coal fly ash leachate. The proposed method provides a fast, sensitive, and efficient method for REE determination, demonstrating significant potential for environmental monitoring and resource recovery.

Castillo et al. investigated the ability of an ionic liquid, R4NCy, to extract multiple metal ions from aqueous solutions. The results show high extraction efficiencies for copper, iron, zinc, and manganese, suggesting the applicability of ionic liquids in pre-treatment processes to remove metal impurities from industrial solutions.

Djokić et al. examined the impact of impurities from e-waste electrorefining on the copper extraction processes. Their optimization of the process parameters revealed strategies to enhance copper recovery while minimizing the co-extraction of other metals, contributing to more efficient e-waste recycling methods.

Cerrillo-Gonzalez et al. summarized an overview of electrodialysis (ED) for metal recovery from wastewater. This review discusses the fundamentals, operational features, and key factors affecting ED performance, highlighting its potential in selective metal recovery and the promotion of a circular economy.

Nastasović et al. reviewed the role of methacrylate-based polymeric sorbents in metal recovery from aqueous solutions. This review emphasizes the versatility, efficiency, and regeneration potential of these sorbents, highlighting their applicability in various environmental and industrial processes.

3. Conclusions and Outlook

The articles in this Special Issue demonstrate significant advancements in the development and application of advanced sorbents for metal-ion separation. From novel silica-based adsorbents and ion-exchange resins to sustainable biosorbents and innovative polymeric materials, the contributions highlight diverse approaches to metal separation. These articles offer prospective options for resource recovery and environmental remediation by shedding light on the synthesis of sorbent materials, elucidating their structure, adsorption mechanism, effectiveness, and process optimization.

Future studies should concentrate on scaling up these sorbent applications, improving their selectivity and efficiency, and incorporating them into encompassing process systems to meet increasing demands for metals and the requirements of environmentally friendly waste management solutions.

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List of Contributions

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