Recovery and Upcycling of Rare Earth Elements

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Rare earth elements are widely used in technological applications such as computers, catalysts, phosphors, batteries of electric cars, and renewable energy production.[1] It has been estimated that the demand of the rare earth elements increases considerably in the future. For example, In EU alone electro mobility and renewable energy production could raise the demand for dysprosium and neodymium up to 12- and 4-fold by 2050 from the current demand of 200 and 4000 tons, respectively.[2] Thus, there has been an increased interest to develop the mining of the rare earth elements as well as to recover the rare earth elements from the waste streams such as mining wastewaters, lamp phosphors waste, and NdFeB magnet waste.[3]

α-Aminophosphonates are organophosphorus compounds that were investigated as extraction agents for the rare earth elements for the first time in the 1960s.[4] However, their more systematic investigations did not start until the 2010s, and recent studies have shown that these α-amino-functionalized compounds can outperform the commercial organophosphorus extraction agents in the recovery of the rare earth elements.[5,6] If one also considers the facile synthesis of α-aminophosphonates from simple starting materials through Kabachnik–Fields and Podovik reactions as well as their stability in acidic solutions, α-aminophosphonates are ideal scavengers for the rare earth elements from various waste streams.

In this talk, I summarize our group's recent findings related to the chemistry of α-aminobis(phosphonates) and discuss their utilization to recover rare earth elements from waste streams.[7,8] Our results show that α-aminobis(phosphonates) are not only suitable precipitation agents for rare earth elements but also good additive materials for 3D printed filters that can be used in the solid-phase extraction of the rare earth elements from waste streams. Moreover, I discuss about the utilization (upcycling) of the recovered rare earth elements as building blocks for novel (molecular) materials exhibiting interesting magnetic and photonic properties.

References

(1) Balaram, V. Rare Earth Elements: A Review of Applications, Occurrence, Exploration, Analysis, Recycling, and Environmental Impact. *Geoscience Frontiers* **2019**, *10* (4), 1285–1303. https://doi.org/10.1016/j.gsf.2018.12.005.

(2) European Commission, Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study, 2020, 1-100.

(3) Binnemans, K.; Jones, P. T.; Blanpain, B.; Van Gerven, T.; Pontikes, Y. Towards Zero-Waste Valorisation of Rare-Earth-Containing Industrial Process Residues: A Critical Review. *Journal of Cleaner Production* **2015**, *99*, 17–38. https://doi.org/10.1016/j.jclepro.2015.02.089.

(4) Jagodić, V.; Herak, M. J. Synthesis and Physical Properties of a Novel Aminophosphonic Acid as an Extracting Agent for Metals. *Journal of Inorganic and Nuclear Chemistry* **1970**, *32* (4), 1323–1332. https://doi.org/10.1016/0022-1902(70)80131-2.

(5) Kukkonen, E.; Virtanen, E. J.; Moilanen, J. O. α-Aminophosphonates, -Phosphinates, and -Phosphine Oxides as Extraction and Precipitation Agents for Rare Earth Metals, Thorium, and Uranium: A Review. *Molecules* **2022**, *27* (11), 3465. https://doi.org/10.3390/molecules27113465.

(6) Amira, A.; Aouf, Z.; K'tir, H.; Chemam, Y.; Ghodbane, R.; Zerrouki, R.; Aouf, N.-E. Recent Advances in the Synthesis of α-Aminophosphonates: A Review. *ChemistrySelect* **2021**, *6* (24), 6137–6149. https://doi.org/10.1002/slct.202101360.

(7) Virtanen, E. J.; Perämäki, S.; Helttunen, K.; Väisänen, A.; Moilanen, J. O. Alkyl-Substituted Aminobis(Phosphonates)—Efficient Precipitating Agents for Rare Earth Elements, Thorium, and Uranium in Aqueous Solutions. *ACS Omega* **2021**, *6* (37), 23977–23987. https://doi.org/10.1021/acsomega.1c02982.

(8) Virtanen, E. J.; Kukkonen, E.; Yliharju, J.; Frimodig, J.; Kinnunen, K.; Lahtinen, E.; Hänninen, M. M.; Väisänen, A.; Haukka, M.; Moilanen, J. O. Recovery of Rare Earth Elements, Uranium, and Iron from Mining Waste Water with Aminomethylphosphonic Acid Functionalized 3D Printed Filters. *Separation and Purification Technology* **2024**, in revision.