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EDITORIAL

Technology-Critical Elements: An Emerging and Vital Resource that Requires more In-depth Investigation

Duc Huy Dang[1] · **Montserrat Filella**[2] · **Dario Omanović**[3]

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Our modern high-technology society and economy are increasingly dependent on so-called technology-critical elements (TCEs). These elements are becoming vital to manufacture components for a wide array of advanced and innovative technologies (e.g., electronics, renewable energy, transport, agriculture, health, military). A raw material is defined as "critical" as per the risk of supply shortages, which has subsequent impacts on the economy and security of nations. According to the most updated classifications, thirty elements and minerals fall into the definition of TCEs by the European Commission, while 35 minerals are deemed critical by the U.S. Department of the Interior (Table 1). It is important to note that the lists of critical materials are not permanent but rather are dynamic and periodically amended in line with (i) the strategic vulnerability to economic impacts for individual countries or economic unions, (ii) military and geopolitical considerations, and (iii) the potential for impacts to the supply chain from natural disasters and other disruptive events (U.S. Department of the Interior 2018; European Commission 2020).

As the TCE categorization is purely based on economic and geopolitical concepts, its usefulness as an organizing framework from environmental or ecotoxicological perspectives is questionable because of the high degree of chemical heterogeneity among these elements (Filella 2020). Nonetheless, TCE categorization aside, studies of the fate and effects of these elements are clearly needed. In addition to direct emissions into the environment through mining, ore processing activities, and fossil fuel combustion, some of these elements are also known for their high dissipative losses from automotive, high-tech products, and various non-point sources (Zimmermann and Gößling-Reisemann 2013), as illustrated in Fig. 1a. Further, the progressively burdensome disposal of manufactured products at end-of-life (e.g., electronic waste, solar panels) could pose potentially severe and unforeseen impacts (Fig. 1b).

Therefore, because of the criticality and the implications of TCEs for impacts upon the economy, the environment, and human well-being, there is a pressing need to develop analytical techniques and sensitive toxicological methods for in-depth investigations of TCEs, especially for providing the necessary data to conduct ecological and human health risk assessments. Within this context, this special issue entitled, "*Environmental Fate and Effects of Technology Critical Elements*" is dedicated to providing insights into the fates and ecotoxicological effects of many of the elements commonly classified as TCEs. The special issue includes two mini-reviews and ten original research articles that collectively present results on the development of novel analytical procedures, geochemical and exposure assessments, and laboratory-based toxicological experiments for selected TCEs.

The two mini-reviews provide a knowledge gap analysis of rare earth elements (REEs) used in agriculture (Tommasi et al. 2020) and a perspective of their circular economy (Dang et al. 2021a). Both highlight the large variety of REE-based applications, their criticality from an economic and geopolitical standpoint, as well as their essential contributions to critical economic sectors. The authors also call for further research on the (eco)toxicological effects of REEs to establish environmental regulations and to weigh the benefits against the risks before extending their use for specific technical purposes in agriculture.

✉ Duc Huy Dang
huydang@trentu.ca

Montserrat Filella
montserrat.filella@unige.ch

Dario Omanović
omanovic@irb.hr

[1] School of the Environment, Department of Chemistry and Water Quality Center, Trent University, Peterborough, ON, Canada

[2] Department F.-A. Forel for Environmental and Aquatic Sciences, University of Geneva, Geneva, Switzerland

[3] Division for Marine and Environmental Research, Ruđer Bošković Institute, Zagreb, Croatia

Table 1 List of critical raw materials, as defined by the European Commission and the U.S. Department of the Interior (US DOI). The total number of elements/minerals is provided in brackets

Elements	European Commission				US DOI
	2011 (14[a])	2014 (20)	2017 (27)	2020 (30)	2018 (35[a])
Antimony	X	X	X	X	X
Arsenic					X
Barite			X	X	X
Bauxite (aluminum)				X	X
Beryllium	X	X	X	X	X
Bismuth			X	X	X
Borate		X	X	X	
Cesium					X
Chromium		X			X
Cobalt	X	X	X	X	X
Coking coal		X	X	X	
Fluorspar	X	X	X	X	X
Gallium	X	X	X	X	X
Germanium	X	X	X	X	X
Hafnium			X	X	X
Helium			X		X
Heavy REEs	X	X	X	X	X
Indium	X	X	X	X	X
Light REEs	X	X	X	X	X
Lithium				X	X
Magnesite		X			
Magnesium	X	X	X	X	X
Manganese					X
Natural graphite	X	X	X	X	X
Natural rubber			X	X	
Niobium	X	X	X	X	X
Phosphate rock		X	X	X	
Platinum group metals[b]	X	X	X	X	X
Phosphorus			X	X	
Potash					X
Rhenium					X
Rubidium					X
Scandium			X	X	X
Silicon metal		X	X	X	
Strontium				X	X
Tantalum	X		X	X	X
Tellurium					X
Titanium				X	X
Tin					X
Tungsten	X	X	X	X	X
Uranium					X
Vanadium			X	X	X
Zirconium					X

[a] Heavy and light REEs referred to as the rare earth element group

[b] or Platinum group elements

The detection of TCEs in the natural environment is a challenging task, given their low concentrations and serious analytical interferences. In this light, Liu et al. (2021) optimized an off-line preconcentration method for REEs in marine porewater and applied this method to porewater extracted from the central Indian Ocean sediments.

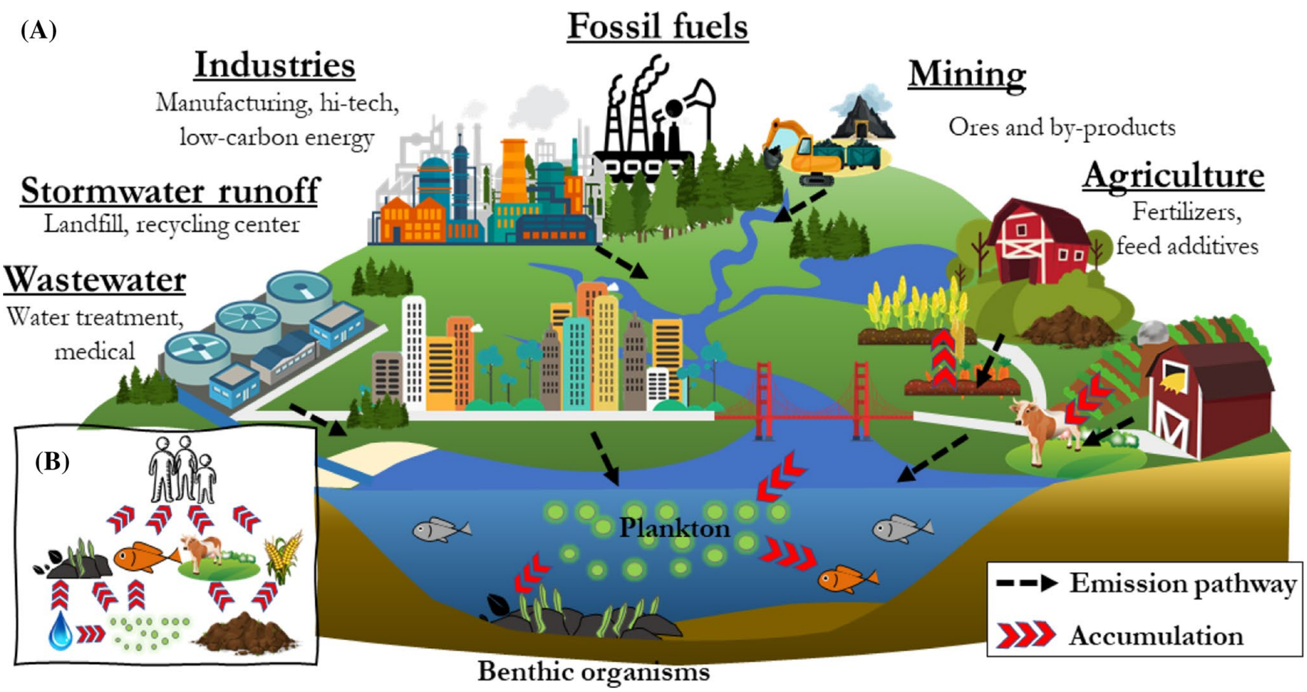

Fig. 1 Major emission sources and pathways for the transport of TCEs in the environment (**a**) and within aquatic/terrestrial food webs (**b**)

Bura-Nakić et al. (2021) coupled a preconcentration method with high-resolution mass spectrometry to detect dissolved Re in the natural environment at pM concentrations. Their approach enabled the assessment of Re geochemical behavior during estuarine mixing and helped identify potential anthropogenic inputs of Re in the Krka river and estuary in Croatia.

Three manuscripts in this special issue document the occurrence, distribution and enrichment mechanisms of TCEs in soils and sediments. Lučić et al. (2020) investigated the geochemical characteristics of several TCEs (i.e., Li, Sc, W, Ga, Ge, Y and the lanthanide series) in soils developed on different geological strata in the catchment of the Sava River in Slovenia and Croatia. Lithology was the first-order control on the composition of the studied TCEs, with the lowest concentrations in carbonate-rich and alluvial soils and the highest abundance in shale and moraine debris. The occurrence and distribution of ten TCEs (i.e., Li, Nb, Sc, Ga, Y, La, Sb, Ge, Te and W) in sediment cores collected from marine and remote freshwater settings were assessed by Bačić et al. (2021). In these systems, while the variations in the vertical profiles of the TCEs were mainly associated with inputs of terrigenous materials (i.e., natural processes), atmospheric deposition could be responsible for the anthropogenic enrichment of a few TCEs, especially Sb and Te. Moreover, coherent biogeochemical processes led to the enrichment of both REEs and U in an ecosystem highly impacted by past uranium mining activities (Dang et al. 2021b). While U accumulation in sediments resulted mainly from biotic reduction associated with sulfate-reducing bacteria, REE enrichment was mostly related to the in situ formation of REE-phosphate minerals. Both processes were intimately related through early diagenesis governing the biogeochemistry at the sediment–water interface.

Another important aspect of evaluating the environmental impacts of TCEs is the assessment of their bioavailability and toxicity. In this special issue, there is a report on the distribution of REEs in the soft tissues of bivalves, as well as articles describing laboratory-based experiments to document the accumulation and toxicity of TCEs to algae, crustaceans, and fish. In marine bivalves, Briant et al. (2021) reported a systematic increase in REEs in bivalves locating near estuarine environments, with different REE patterns in two species of mussels (*Mytilus edulis, Mytilus galloprovincialis*) relative to the pattern in oysters (*Crassostrea gigas*). Aharchaou et al. (2020) investigated the bioavailability and uptake of Gd in green algae (*Chlamydomonas reinhardtii*) and reported the lack of competition from Al and Fe but competitive effects among the lanthanides. In a similar fashion, the acute toxicity of another REE, Tm, to an amphipod crustacean (*Hyalella azteca*) appeared to not be modified by the presence of major cations but rather was affected by the formation of organic complexes (McGeer et al. 2021). Lastly, the redox chemistry of antimony (i.e., Sb^{III} and Sb^{V}) significantly affected the lethal responses of exposed Australian bass (*Macquaria novemaculeata*) and silver perch (*Bidyanus bidyanus*), possibly by affecting rates of uptake (Obiakor et al. 2021).

Extraction and refining of TCEs from both primary and secondary sources are well known for severe environmental and human health consequences. Moreover, besides the risks of contamination and exposure to the ores and mineral components in mine tailings, exposure to ionizing radiation might also be a significant risk factor. Ore bodies for the mining of tantalite (Ta) and columbite (Nb) can contain the radionuclides, e.g., U and Th, and their decay products. Carvalho et al. (2021) investigated the risks of human exposure to radiation associated with tantalite mining in Ethiopia and confirmed that there were risks associated with the high concentration of various radionuclides in rock materials, and especially in the tantalite concentrate.

As the global use of TCEs increasingly impacts the environment and the well-being of humankind, it is vital to better document the concentrations, chemical speciation (or bioavailability), toxicological thresholds and capacity for biomagnification of TCEs to assist scientists, policymakers, industrial and social stakeholders in transitioning to a sustainable economy that is reliant on TCEs. The articles included in this special issue provide new insights into the analysis, environmental cycling and effects of TCEs and contribute to a better understanding of the factors that govern the environmental fate and (eco)toxicological effects of these critical elements.

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Declaration

Conflict of interest The authors declare that they have no conflicts of interest related to this editorial article.

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