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Editorial

# Editorial: microbes vs. metals: harvest and recycle

Microbes and metals are intricately linked in a complex relationship. Many microbial pathways rely on metals for functionality, including enzymatic machinery (co-factors in key enzymes), dissimilatory reduction in energy generation (as alternative electron acceptors in anaerobic respiration) and biomineralization. Some metals share very close physical–chemical properties, thus sensing and incorporating the right metal in enzymes can be a finely-tuned, tightly regulated process (Waldron and Robinson 2009). In environments where essential metals have limited bioavailability microbes have developed high-affinity chelators (metallophores) or are capable of changing the redox conditions at the microscale level to solubilize them. The production of cellular energy using the redox-state transformations of metals/metalloids is an ancient strategy some bacteria and archaea use to sustain growth under nutrient-poor and sometimes extreme conditions (Stolz and Oremland 1999; Gescher and Kappler 2012; Staicu and Barton 2017; Wells *et al.* 2020). Biominerals are synthesized by microbes to alleviate metal stress and to serve diverse ecological functions (e.g. magnetotactic bacteria synthesize particles of single-domain magnetite de novo, providing them the ability to sense and orient in the ambient geomagnetic field). Metals can be toxic and microbes have developed sophisticated resistance mechanisms to counteract this type of stress. Strategies include ion specific efflux pumps, sequestration in poorly soluble minerals and redox change reactions (Nies 1999; Ni *et al.* 2015).

Metals are also key to human health, culture and industrialization. The typical multivitamin supplements contain a host of metals including selenium, copper, nickel, zinc, manganese and molybdenum, again a reflection of the presence of metalloenzymes and their co-factors. Metals have played a crucial role in human history (e.g. iron age and bronze age), and today more than ever, our daily life cannot be sustained without metals, from energy production and storage, transport, building and maintaining infrastructure or to technology. Mobile phones, which have revolutionized how people communicate, contain iron, nickel, gold, silver, platinum, palladium, aluminum, tin and copper (Sullivan 2006). While some metals are still abundant, the projected demand for others will outstrip supply in the foreseeable future, thus being listed as critical raw materials (CRMs) by various agencies and by the European Commission (https://ec.europa.eu/). In contrast to the renewable energy, metals are not at a practical time scale, therefore their use should be sustainable. Further, there is growing concern over the proliferation of 'e-waste' (i.e. discarded electronic devices, computers and cell phones). This means new strategies have to be implemented for efficient recovery, reuse and for metal extraction from low-grade resources (e.g. metalliferous soils, metallurgical slags and mine waste; Vidal *et al.* 2017; Kisser *et al.* 2020). Microbes and their capacity to transport metals can be of great use in such a context as this approach offers a less energy-intensive and also a less environmentally-degrading alternative to processes such as hydro- and pyrometallurgy. Biomining and bioleaching, the recovery of metals using microbial metabolism, are successfully used in industrial operations for the extraction of copper, gold and uranium (Jerez 2017). This strategy can be applied to both metal-rich deposits as well as to low-grade metal wastes/slags resulted from past industrial activities and discarded in the environment (Potysz and Kierczak 2019). Another unexploited source is the metal-rich wastewater generated by numerous industrial activities. Such sources, in the framework of the growing circular economy paradigm shift, started to be regarded as a resource rather than a waste material. These industrial streams can be treated using a microbially-mediated bioremediation approach, coupled with metal recovery (Puyol *et al.* 2016). It may also be possible to recover metals from printed circuit boards of computers and cell phones (Argumedo-Delira, Diaz-Martinez and Gomez-Martinez 2020). Thus, we thought it timely to have a themed issue 'Microbes vs Metals: Harvest and Recycle'.

We have assembled a group of papers with a range of topics covering various chemical elements such as antimony, arsenic, copper, gold, iron, lead, manganese, selenium, tellurium, thallium and alloys (steel). They include contributions on metal resistance (Cyriaque *et al.* 2020; Sanyal, Reith and Shuster 2020; Yasir *et al.* 2020; Butz *et al.* 2021; Xu *et al.* 2020), biomineralization (Staicu *et al.* 2020), microbial ecology (Sjöberg *et al.* 2020; Taleski *et al.* 2020; Garrison and Field 2021; Zhang *et al.* 2021), as well as several review articles (Oremland 2020; Wells and Stolz 2020; Giachino *et al.* 2021; Mergeay and van Houdt 2021). Overall, the above-mentioned contributions demonstrate the complex relationship microbes have with chemically-diverse elements from the periodic table, from transition and precious metals to metalloids and alloys. Either as pure cultures or as mixed microbial communities, microbes are able to colonize and modify diverse environments, thus impacting the mobility and biogeochemical cycles of the elements in nature. From a technological perspective, microbes act as cleaning agents in industrially-polluted environments, being exploited in approaches that are less aggressive than the conventional treatment systems.

This themed issue is also dedicated to one of the pioneers of geomicrobiology, Professor Henry L. Ehrlich, whom we lost in 2020. Professor Ehrlich was known not only as an expert

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in microbial manganese metabolism, but also a great mentor, teacher and source of inspiration (Ghiorse 2020).

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***Conflicts of Interest.*** None declared.

## REFERENCES

Argumedo-Delira R, Diaz-Martinez ME, Gomez-Martinez MJ. Microorganisms and plants in the recovery of metals from printed circuit boards of computers and cell phones: a mini review. *Metals* 2020;**10**:1120.

Butz Z, Hendricks A, Borgognoni K *et al*. Identification of a $TeO_3^{2-}$ reductase/mycothione reductase from *Rhodococcus erythropolis* PR4. *FEMS Microbiol Ecol* 2020;**97**:fiaa220. DOI: 10.1093/femsec/fiaa220.

Cyriaque V, Géron A, Billon G *et al*. Metal-induced bacterial interactions promote diversity in river-sediment microbiomes. *FEMS Microbiol Ecol* 2020;**96**:fiaa076. DOI: 10.1093/femsec/fiaa076.

Garrison CE, Field EK. Introducing a “core steel microbiome” and community functional analysis associated with microbially influenced corrosion. *FEMS Microbiol Ecol* 2020;**97**:fiaa237. DOI: 10.1093/femsec/fiaa237.

Gescher JG, Kappler AK. *Microbial Metal Respiration*. Berlin Heidelberg: Springer-Verlag, p. 236, 2012.

Ghiorse WC Three collective memories of Henry L. Ehrlich. *FEMS Microbiol Ecol* 2020;**96**:fiaa120. DOI: 10.1093/femsec/fiaa120.

Giachino A, Focarelli F, Marles-Wright J *et al*. Synthetic biology approaches to copper remediation: bioleaching, accumulation, and recycling. *FEMS Microbiol Ecol* 2021;**97**:fiaa249. DOI: 10.1093/femsec/fiaa249.

https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

Jerez CA. Biomining of metals: how to access and exploit natural resource sustainably. *Microb Biotechnol* 2017;**10**:1191–3.

Kisser J, Wirth M, De Gusseme B *et al*. A review of nature-based solutions for resource recovery in cities. *Blue Green Syst* 2020;**2**:138–72.

Mergeay M, van Houdt R. *Cupriavidus metallidurans* CH34, a historical perspective on its discovery, characterization and metal resistance. *FEMS Microbiol Ecol* 2021;**97**:fiaa247. DOI: https://doi.org/.

Nies DH. Microbial heavy-metal resistance. *Appl Microbiol Biotechnol* 1999;**51**:730–50.

Ni TW, Staicu LC, Nemeth R *et al*. Progress toward clonable inorganic nanoparticles. *Nanoscale* 2015;**7**:17320–7.

Oremland RS. Got Selenium? *FEMS Microbiol Ecol*. 2020;**96**:fiaa094. DOI: 10.1093/femsec/fiaa094.

Potysz A, Kierczak J. Prospective (bio)leaching of historical copper slags as an alternative to their disposal. *Minerals* 2019;**9**:542.

Puyol D, Batstone D, Hulsen T *et al*. Resource recovery from wastewater by biological technologies: opportunities, challenges and prospects. *Front Microbiol* 2016,**7**:1–23.

Sanyal SK, Reith F, Shuster J. A genomic perspective of metal-resistant bacteria from gold particles: possible survival mechanisms during gold biogeochemical cycling, *FEMS Microbiol Ecol* 2020;**96**:fiaa111. DOI: 10.1093/femsec/fiaa111.

Sjöberg S, Stairs CW, Allard B *et al*. Microbiomes in a manganese oxide producing ecosystem in the Ytterby mine, Sweden: impact on metal mobility. *FEMS Microbiol Ecol* 2020;**96**:fiaa169. DOI: 10.1093/femsec/fiaa169.

Staicu LC, Barton LL. Microbial metabolism of selenium – for survival or profit. In: van Hullebusch ED (ed.) *Bioremediation of Selenium Contaminated Wastewaters*, Springer, 2017, pp. 1–31.

Staicu LC, Wojtowicz PJ, Pósfai M *et al*. PbS biomineralization using cysteine: *b acillus cereus* and the sulfur rush. *FEMS Microbiol Ecol* 2020;**96**:fiaa151. DOI: 10.1093/femsec/fiaa151.

Stolz JF, Oremland RS. Bacterial respiration of arsenic and selenium. *FEMS Microbiol Rev* 1999;**23**:615–27.

Sullivan DE, *Recycled cell phones – a treasure trove of valuable metals*, US Geological Survey, Fact Sheet 2006–3097, US Geological Survey, 2006.

Taleski V, Dimkić I, Boev B *et al*. Bacterial and fungal diversity in the lorandite (TlAsS2) mine ‘Allchar’ in the Republic of North Macedonia. *FEMS Microbiol Ecol* 2020;**96**:fiaa155. DOI: 10.1093/femsec/fiaa155.

Vidal O, Rostom F, Francois C *et al*. Global trends in metal consumption and supply: the raw material-energy nexus. *Elements* 2017;**13**:319–24.

Waldron KJ, Robinson NJ. How do bacterial cells ensure that metalloproteins get the correct metal? *Nat Rev Microbiol* 2009;**7**:25–35.

Wells M, Kanmanii NJ, Al Zadjali AM *et al*. Methane, arsenic, selenium and the origins of the DMSO reductase family. *Sci Rep* 2020;**10**:10946.

Wells M, Stolz JF. Microbial selenium metabolism: a brief history, biogeochemistry and ecophysiology, *FEMS Microbiol Ecol*. 2020;**96**:fiaa209. DOI: 10.1093/femsec/fiaa209.

Xu R, Sun X, Lin H *et al*. Microbial adaptation in vertical soil profiles contaminated by an antimony smelting plant. *FEMS Microbiol Ecol* 2020;**96**:fiaa188. DOI: 10.1093/femsec/fiaa188.

Yasir M, Zhang Y, Xu Z *et al*. NAD(P)H-dependent thioredoxin-disulfide reductase TrxR is essential for tellurite and selenite reduction and resistance in *Bacillus* sp. Y3, *FEMS Microbiol Ecol* 2020;**96**:fiaa126. DOI: 10.1093/femsec/fiaa126.

Zhang M, Kolton M, Zhe Li *et al*. Bacteria responsible for antimonite oxidation in antimony-contaminated soil revealed by DNA-SIP coupled to metagenomics. *FEMS Microbiol Ecol* 2021;**97** . DOI: 10.1093/femsec/fiab057.

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