RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

ESSAY

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Cite this: *RSC Sustainability*, 2023, **1**, 1599

DOI: 10.1039/d3su90039h

rsc.li/rscsus

Science – a chess game against time

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On occasion, I enjoy the odd chess game. I enjoy the logic of it, but even more so the strategy behind every move. While practising some openings, it recently occurred to me that my responsibility as a scientist towards the environment and society is not so different to a chess game. In chess the playing board needs to be continually assessed, patterns need to be recognized and the next few steps need to be considered and planned. Scientists must do the same with regard to the environment – data is collected, and patterns are recognized and identified as forebearers to crises. Then plans need to be made to either circumvent or overcome them. One familiar example is global warming, which was discussed in the literature already in the early 1900s. At this point, the data was collected, and the pattern was tentatively identified. However, it took humanity a good century to appropriately address the issue. One strategy to prevent this crisis from escalating further is investing in alternative technologies to become carbon-neutral and move away from fossil fuels. Major solutions are alternative energy sources such as solar, wind, and hydropower. Despite these being excellent solutions to the problem at hand, they might be the initiator for the next crisis that we need to navigate: the shortage of critical elements.

Critical resources, in the broadest sense, are those resources which are essential to sustain and further develop a society. Levels of development and lifestyles differ drastically amongst regions; thus, the critical resources vary as well. Nonetheless, globalization is causing critical resources to overlap increasingly amongst different societies. In the current technological age, regardless of the economic status of an area, these mainly include the later transition- and post-transitional metals, but also the lanthanides and a few odd elements throughout the periodic table.[1,2] Modern technologies, like those implemented as alternative energy sources, rely heavily on these elements for their production. The importance is, however, not the only reason these count as critical, but rather the demand and therefore the rate at which they are mined and refined.[1] In 2021, over 1.4 billion smartphones were sold worldwide.[3] The precious metals in these products alone add up to

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a staggering 47 600 kg of gold, 476 000 kg of silver, 21 000 kg of palladium, and 1400 kg of platinum. An additional 35 million kg of aluminium and 21 million kg of copper are built into these items (according to the data from the BBC, World Changing Ideas Summit).[4] This represents only a tiny fraction of the technologies that require many of the critical elements – keyboards, laptops, industrial robots, batteries, inverters, solar panels and cars are but a few additional examples. The global movement towards a technological and energy revolution is increasing the demand drastically.

According to Hunt, at the current rate of mining, many of the known elemental reserves will have run out in 5–100 years.[1] Thereafter we will be forced to turn to alternatives, such as finding elements which may fulfil the same application and function. For many of the transition and rare earth metals, with their unique chemical properties, this will be close to impossible. Another alternative may be found in the law of conservation of matter which states that within a closed system, no matter can be lost. Earth is such a closed system, within the atmosphere, matter can undergo changes, but not be lost. This silver lining implies that the amount of critical elements available to us will never change. However, as both Brooks and Goeller already described in the mid-70s, the sources of many of these minerals will become increasingly more dilute and consequently challenging to mine or extract. First, the sources that are at high concentrations will be mined to extinction, and then the regions with more dilute concentrations will become of interest to the mining industry.[5,6] Energy requirements to mine the same amount of element will of course be drastically influenced and accordingly the associated costs as well. The real issue at hand is therefore not the limitation of these elements but rather the degree to which they may be mined at reasonable prices.

An intriguing advancement to potentially combat this issue is the application of microfluidic processes in the mining sector. Le *et al.* outlined how these flow chemistry-based processes have the potential to reduce processing time, decrease equipment footprint and increase extraction efficiency, therefore, making the processes both greener and economically more appealing.[2] Flow chemistry has already gained a lot of attention in the pharmaceutical industry. For this reason, a lot of the grunt work in the development of parts and reactors has already been done, making applications to other industries easier and faster. Applications in the mining industry have been successfully tested at a laboratory scale. Most studies have shown that due to the increased surface-to-volume ratio and greater control over heat- and mass-transfer, extraction and refinement steps could be achieved at a higher rate and with improved efficiency. Scale-up to larger processes, where complex ore mixtures need to be processed, still are to be tested. Regardless, the research looks promising, and these microfluidic processes have the potential to make mining of low-quality ores not only cheaper but also safer for workers as contact with hazardous chemicals is reduced.[2]

If this technology can be successfully implemented, it has the capability to expand the sources of critical elements even further. The natural deposits in the Earth's crusts will inevitably become increasingly difficult to mine. Therefore, alternative sources will grow in importance. All the elements that are being mined are conserved in the environment, they are merely getting spread throughout. Tons of important materials, including many critical elements, are being dumped in wastewater and waste yards on a daily basis. One may argue that there will come a time when waste will become one of the most important sources of critical elements. In 1974, Brooks and Andrews noted in their article in *Science* that "natural materials do not become resources until they are combined with man's ingenuity".[5] Today this claim may be made about waste – waste will become a resource if combined with man's ingenuity. Due to its advantages in extraction efficiencies, flow chemical reactors have the prospect to extract minute amounts of elements from mine tailings and leach solutions, aiding in the recycling of industrial waste.[2]

More critical elements are, however, still present in municipal waste. Although recycling is gaining in popularity, many technologies are still extremely complex to recycle and thus it is not economically viable to do so. In many cases, the effort and costs associated with dismantling the item overshadow all environmental gains. At this point in time, it is not yet lucrative enough to invest in recycling, as mining and exploiting nature for these critical elements is still too easy and cheap. Thompson *et al.* advocated for recycling-centered product design in the context of lithium-ion batteries.[7] Recycling-centered design is the idea of developing the product with a cyclic economy in mind and already incorporating measures to disassemble it into reusable parts. This type of thinking is still very foreign but should not only be applied to the hardware but also to the chemistry of products, as well as chemical reactions. It is crucial that chemical scientists consider the end of life of the chemicals and products developed and used in laboratories. Furthermore, chemists are the experts in elements and are hence irreplaceable in the conquest to develop and refine recycling methods which make recycling in general, but especially of critical elements, more economically viable.

Chemical scientists can only be true leaders in stewarding the sustainability of critical elements if they take ownership of the growing issue. This means to act accordingly in their own laboratory but more so to inform peers and the public about this matter. True change only takes place if everyone is on board to achieve it. Interdisciplinary collaborations on both the development of improved technologies, such as microfluidic devices, designed for a sustainable future, but also the legislature are crucial. In this process, a cyclic economy should become the golden standard of all research and development. Furthermore, it is essential that the next generation is trained to think holistically to come up with long-term solutions that address the myriad of environmental challenges we are currently facing. This generation needs to be trained early on to think like chess players – analyzing the data, recognizing future crises, and acting accordingly to prevent them. As the current generation we should learn from the mistakes of those before us, which means we need to act before the crises get out of control. The time to enter the 'age of sustainability' and put elemental scarcity in checkmate is now.

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