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GUEST EDITORIAL

The simple matter of sustainability

We have grown accustomed to thinking that the Earth provides a virtually limitless source of key natural resources from which we can derive all the materials we need. However, designation of 2019 as the International Year of the Periodic Table of Chemical Elements by the United Nations reminds us that there are merely about 100 elemental building blocks in the world. Our planet holds a finite supply of these elements – and we are close to running out of some, while using others in ways that damage the planetary systems that support us.

This International Year recognizes the success of chemistry in unmasking and learning to manipulate the fundamental atomic and molecular entities of which all matter is composed. It marks 150 years since the Russian chemist Dmitry Mendeleev (1834–1907) placed the approximately 60 elements that were then known to exist, into a chart that recognized periodic trends in their relationships. Importantly, Mendeleev used the recognition of these trends to identify gaps in his table and correctly predicted the properties of elements yet to be discovered, including gallium, germanium, scandium and technetium. Since then, the number of elements in the periodic table has swelled to 118. However, the last couple of dozens added are all very unstable radioactive elements with short half-lives, synthesized when atoms collide at high energy. So, the importance of the periodic table is not only that every chemistry student learns to use it to guide understanding of the periodic relationships of element properties and reactions. It also teaches us that no new stable elements are expected. We cannot hope for any new building blocks for the materials of our world and must learn to make the best use of those remaining.

The abundance of elements on the Earth varies greatly and some are already in short supply (Figure 1).

The American Chemical Society (ACS) estimates that 44 of the elements will face supply limitations in the coming years. The list of these critical elements includes the rare earth metals – a set of 17 elements consisting of the 15 lanthanides as well as scandium and yttrium. They are of considerable economic importance and have been increasingly used in recent years in low-carbon technologies, high-performance magnets, catalysts, alloys, glasses and electronics. Other elements in this list include precious metals and some that are vital for life, like phosphorus. To maintain a steady supply of these essential elements, there is an urgent need to reframe our present understanding of mining and consumption, along with environment and waste management (Chattopadhyay, D., *Resonance*, 2017, **22**, 79–87).

Within the broader list, there is a particularly serious threat to the supply of nine elements within the next 100 years and a rising threat due to increased use of a further seven. These 'endangered elements' include common metals like zinc (used to protect iron and steel against corrosion) as well as less abundant elements like tellurium and hafnium (used in electrical devices), indium (a common ingredient of solar cells and computer displays) and the rare earth element neodymium (an important building block of magnets used in many industries). Most of the planet's known supply of lithium is located in just three countries – Argentina, Bolivia and Chile. The large and growing use of this metal in lithium-ion batteries for a wide range of applications, including powering smartphones and electric cars, is creating a global shortage. The average smartphone may contain 60–70 different elements in simple or compound forms.

For another group of elements, the critical challenge is not a shortage of abundance or availability, but the scale and nature of their uses. The concept of 'planetary boundaries' has helped focus attention on the ways that massive uses of elemental resources influence the environment through biogeochemical flows. Nitrogen, comprising more than three-quarters of the Earth's atmosphere, is not in short supply – but atmospheric nitrogen is present in a molecular form that is relatively inert chemically. The German chemists Haber and Bosch learned about a century ago how to make nitrogen and hydrogen react to form ammonia, establishing the basis for a global fertilizer industry. This helped to massively expand agricultural production in the 20th century, while the Earth's population was quadrupling (http://vaclavsmil.com/wp-content/uploads/Smil_SciAm_N2cycle.pdf). However, the costs have included increased concentrations of nitrogen oxides in the atmosphere causing air pollution and increased nitrate concentrations in rivers, lakes and seas that have destroyed habitats for aquatic life. Phosphorus is also essential for life and an important ingredient of many agricultural fertilizers. As with nitrogen, the biogeochemical

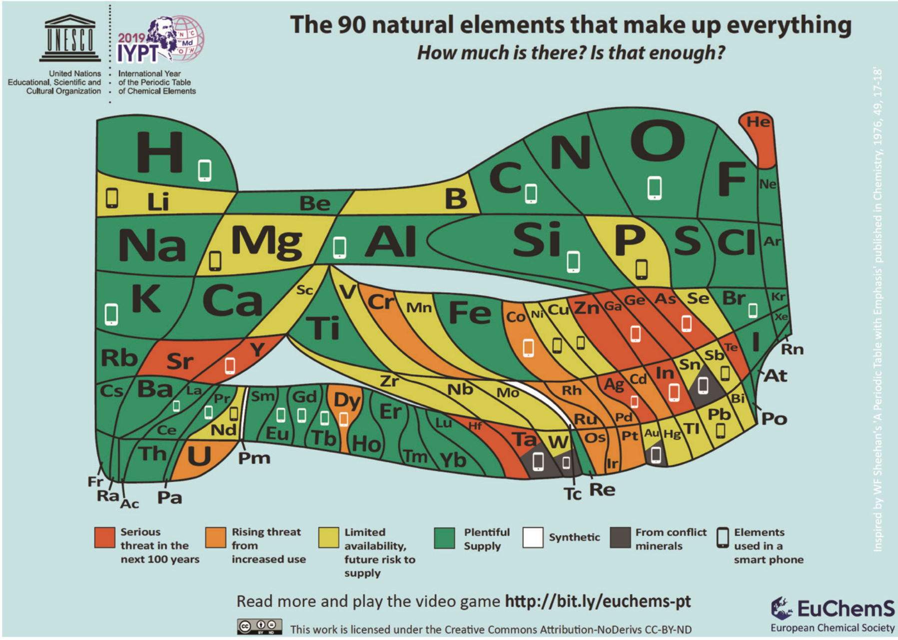

Figure 1. Periodic table of the chemical elements for the International Year (2019), illustrating limitations in element supplies.

flow of phosphorus has also become unsustainable, with a shortage of supply looming and environmental damage growing from the run-off due to fertilizer use. Carbon is available virtually everywhere in the Earth's crust in forms that range from elemental carbon like graphite and diamond, to energy generators in the form of coal and fossil fuels and complex, life-sustaining molecules like proteins and DNA. The massive amount of carbon dioxide which has been emitted into the atmosphere since the Industrial Revolution, due to burning carbon-rich materials, has already created a pathway to global warming, as well as causing ocean acidification that is destroying key ecological habitats like coral reefs.

Husbanding the critical elements, conserving and recycling available supplies of the rare ones and finding new substitutes are essential. This will help mitigate risks of shortages and move industry towards sustainable supply chains. We can also reduce the use of more abundant elements to a minimum, while paying much more attention to a system's view that considers the entire cycle of use, by-products, waste and disposal, in order to prevent damage to our planetary environment. The field of 'green chemistry' (or 'sustainable chemistry') emerged in the 1990s in the context of increasing attention to the overlapping problems of chemical pollution and resource depletion.

Ensuring the sustainability of our planet requires that we urgently learn how to be better stewards of the Earth's limited stock of simple elemental building blocks, to husband them and use them more sensitively and efficiently. Celebration of the International Year of the Periodic Table of Chemical Elements in 2019 is a timely reminder to pay urgent, solution-centric, systems-based attention to this issue. Chemistry, as the science that provides fundamental understanding of the molecular basis of sustainability, is well positioned and central to making this better stewardship possible.

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