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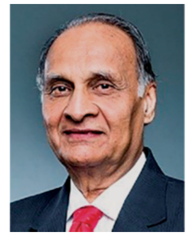
Essay

Elements and Sustainability

The Periodic Table of the Chemical Elements and Sustainable Development

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Abstract: The Periodic Table of the Chemical Elements, central to the field of chemistry, also carries a message of broad societal significance. It conveys a stark warning about the limits of the element stock of our planet and the dangers of excessive and inappropriate utilisation that are a threat to sustainable development.

The Table reminds us that there are less than 100 stable elements on our planet (as well as a couple of dozens of radioactive ones) from which to derive all the materials that are required for life and for well-being and comfortable living. We need to ensure that the finite stocks of these are not excessively depleted or used in environmentally damaging ways. The designation by the UN of 2019 as the International Year of the Periodic Table of Chemical Elements[1] provides a timely opportunity to reflect on this warning and consider how best to meet the challenge it presents.

The International Year marks the 150th anniversary of the publication by the Russian chemist Dmitry Mendeleev (1834–1907) of his Periodic Table[2] and celebrates the significance and impact of this outstandingly successful chart of the atomic building blocks of matter. This was an innovative advance in classification which has helped guide the understanding of chemistry and has spurred on advances in the theoretical understanding of atomic structure.[3] Mendeleev was not the first to publish listings of the known elements in a table but, building on and surpassing the earlier efforts, he rigorously applied the available knowledge of periodic trends in the relationships between the then approximately 60 known elements to produce a chart in which there were gaps at some points. From his Periodic Table Mendeleev predicted the properties of then unknown elements such as gallium (element 31), germanium (32), scandium (21) and technetium (43), represented by the gaps, which were later discovered,[4] and subsequently others like Henry Moseley[5] continued to extend the Periodic Table through predictions and by filling the gaps.

The underlying justification for the structure of the Periodic Table emerged only many years later when atomic structure became understood and atomic number (i.e. the number of nuclear protons, equivalent to the element number), rather than atomic weight, became the recognised basis for ordering its members. Discoveries of new elements and the evolving theoretical understanding of atomic structure eventually resulted in addition of new lanthanide and actinide blocks to the table illustrating the flexibility of the classification system to adapt.[6]

The abiding preeminent position of the Periodic Table in displaying the known elements (now 118) reflects the extent to which the underlying principles on which it is constructed constitute, in effect, a "standard model" for chemistry. The fundamental insight represented by Mendeleev's 1869 classification framework remains intact, although new interactive online[7]and three-dimensional[8,9] presentations emerge. Current research on superatoms (clusters of atoms having properties of a single atom of another element)[10] has led to proposals for multidimensional Periodic Tables to display the relationships.[11]

The last couple of dozens of elements added to the Periodic Table have been created synthetically by very high-energy processes. They are all radioactive, decaying by fission into lighter

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elements with half-lives ranging from fractions of a second (e.g. element 118, oganesson ^{294}Og, has a half-life of less than 1 millisecond) to millions of years (e.g. element 96, curium ^{247}Cm). It is not expected that any new stable elements will be discovered on Earth,[12] although small amounts of new radioactive elements will continue be synthesised and "super-heavy" ones may be formed in astronomical events such as supernovas and neutron star collisions. However, for everyday use, there will be no new stable building blocks from which to fashion the materials of our world. We must learn to make the best use we can of those elements we have, based on the understanding that geological resources are finite and not renewable.

The vast majority of the known, stable elements are of central importance to us, biologically, technologically and/or economically. At least 60 elements can be detected in trace amounts or more in the human body, and about 28 of these – a quarter of the Periodic Table – are thought to play an active positive role in the life and health of humans.[13,14] While carbon, hydrogen, oxygen, nitrogen, phosphorus and calcium make up almost 99 % of the human body, molecules and complexes containing small amounts of the remaining elements utilised are involved in a wide range of metabolic functions, including as enzymes, catalysts and transporters (e.g. iron in haemoglobin, which carries oxygen and carbon dioxide). In addition to using the same major building blocks, other organisms may utilise some different elements in their biochemical processes (e.g. magnesium in chlorophyll, which fixes oxygen in plants).

There are great variations in the total abundance of the Periodic Table's contents in the Earth's crust (Figure 1) and, very importantly, also great variations in the distribution of the elements. While some of the most abundant are very widely distributed in the Earth's atmosphere, land and oceans, others are concentrated in relatively few locations.

Developing technology for the exploitation of mineral ores has been a constant feature of human history and increasing use of different elements has been a major driver of economic growth since the Industrial Revolution – and, in tandem with expansions in mining and refining, there has been a growing technological capacity to exploit the unique characteristics of certain elements that were hitherto poorly available. Advances utilising diverse elements have provided benefits such as stronger magnets that are used in many industries (e.g. using the rare earth metals neodymium and dysprosium), smaller microprocessors (e.g. gallium and germanium), more efficient solar cells (e.g. gallium, indium and tellurium) and touchscreens (indium, niobium). Many modern devices use a very wide range of elements and compounds derived from them. General Electric, one of the world's largest companies, uses 72 of the first 82 elements of the Periodic Table in its product lines, and many of these elements are rare or difficult to obtain.[15] In another example, relating to a single type of product, at least 70 elements, in simple or compound forms, can be found in the average smartphone.[16]

A growing awareness of the limited supplies of some elements that have specialised and important uses is reflected in the proliferation of terms to describe them and the ores from which they are derived, including "gateway minerals", "critical elements" and "endangered elements".[17,18] Some countries have adopted policies that take account of the high strategic

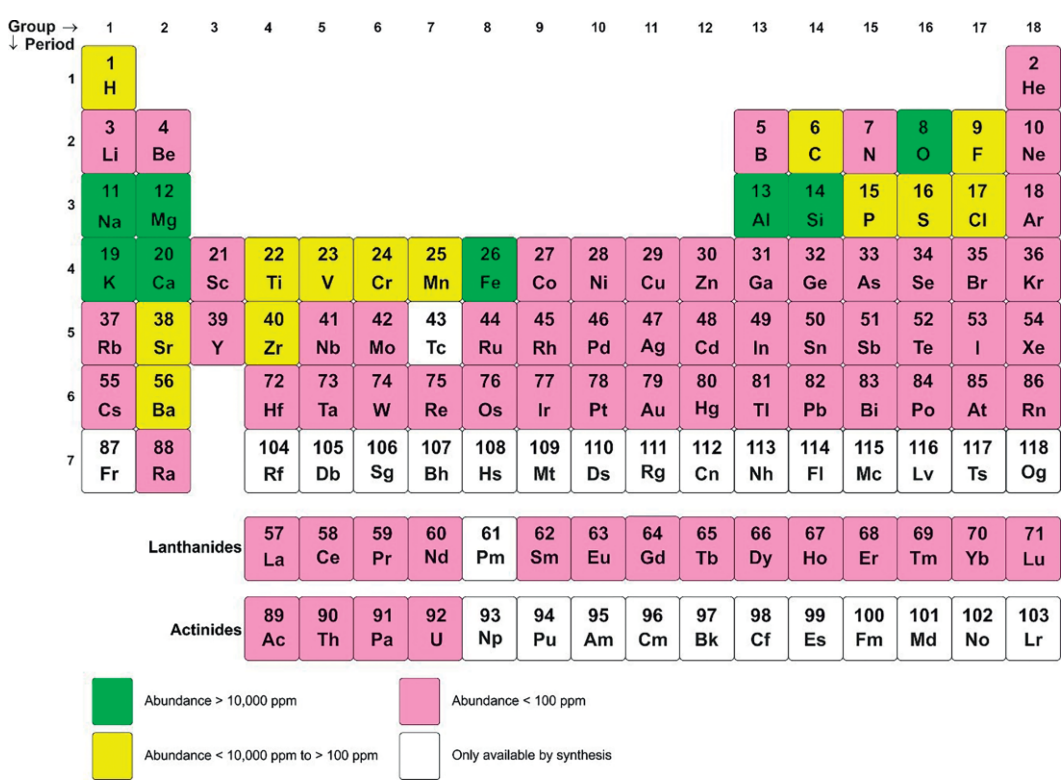

Figure 1. Abundance of elements in the Earth's crust (drawn from data available on the Royal Society of Chemistry Website: Periodic Table[7]).

Table 1. Planetary boundaries (data from ref.[22]).

Planetary boundary — Threshold

Variable:	Indicator measured	Below boundary (safe)	In zone of uncertainty (increasing risk)	Beyond zone of uncertainty (high risk)	Boundary not yet quantified globally	Planetary boundary	Value of control variable (2015)
Atmospheric aerosol loading:	Aerosol Optical Depth (AOD), but much regional variation					Not yet quantified	0.30 AOD over South Asian region
Biogeochemical flows:	Nitrogen: industrial & intentional biological fixation					N: 62 Tg/yr	c. 150 Tg/yr
	Phosphorus: flow from freshwater systems into ocean					P: 11 Tg/yr	c. 22 Tg/yr
Change in biosphere integrity:	Genetic diversity (extinction rate)					<10 extinctions per million species-years (E/MSY)	100-1000 E/MSY
	Functional diversity (Biodiversity Intactness Index)					Maintain Biodiversity Intactness Index (BII) at >90%	BII at 84% in southern Africa
Climate change:	Atmospheric CO_2 concentration					350 ppm	398.5 ppm
Freshwater Use	Maximum amount of consumptive blue water use ($km^3\,yr^{-1}$)					4000 $km^3\,yr^{-1}$	c. 2,600 $km^3\,yr^{-1}$
Land-system change	Area of forested land as % of original forest cover					75 %	62 %
Novel entities In environment:	Chemical pollution					No boundary currently identified.	See stratospheric ozone for example of boundary related to a novel entity (CFCs)
Ocean acidification	CO_3^{2-} concentration, average global surface ocean saturation state with respect to aragonite					≥80 % of pre-industrial aragonite saturation state of mean surface ocean	c. 84% of pre-industrial aragonite saturation state
Stratospheric ozone depletion:	Stratospheric O_3 concentration, Dobson Units (DU)					<5% reduction from preindustrial level of 290 DU, assessed by latitude	Only transgressed over Antarctica in Austral spring (c. 200 DU)

importance of some of these for their physical and economic security.[19,20]

While increasing attention is rightly being given to the risks of material scarcity, a parallel problem of considerable urgency concerns the impact of massively expanding use of relatively abundant elements. An important approach to framing this issue has been the development of the concept of planetary boundaries, first advanced by Rockström, Steffen and colleagues in 2009 and further elaborated in 2015.[21,22] Boundaries that relate to nine Earth system processes of critical importance for sustainable development have been proposed, and in most cases the work has already defined a quantitative "safe operating space for humanity", a threshold region in a "zone of uncertainty", where there is increasing risk, and beyond this a "zone of high risk" of major and long-term damage to the planetary environment (Table 1).

Three of the boundaries concern biogeochemical flows of key elements that are relatively abundant in either the Earth's crust (carbon: 0.18 %; phosphorus: 0.1 %) or atmosphere (nitrogen: 0.002 % in the crust and 78 % of the atmosphere). The key problem in each case relates to the extent to which industrial uses are contributing to major environmental changes. For example:

- Generation of greenhouse gases from combustion of carbon-rich materials to produce energy is contributing to climate change. The atmospheric concentration of CO_2 is already well into the threshold region where there is an increasing risk of global warming. Having increased by about 40 % globally since the Industrial Revolution, the atmospheric CO_2 level flattened out[23] in 2014–2016 before rising again in 2017–2018 due to increased use of oil and gas.[24]
- The Haber–Bosch process for the fixation of atmospheric nitrogen as ammonia and the production of ammonium nitrate and other N-containing fertilisers was extremely important in helping to raise agricultural yields and feed the burgeoning world population in the 20th century.[25] However, pollution of the Earth's atmosphere and water by nitrogen oxides and nitrates is estimated to have exceeded the planetary boundary for reactive nitrogen species by about two and a half times.
- In parallel with the increased use of nitrogen, there has been a complementary increase in the use of phosphorus, particularly in phosphate fertilisers, with a concomitant rise in pollution of water due to agricultural run-off. At the present scale of use, it is predicted there will be a shortage of phosphates in the next 50 to 150 years and the need for "phosphorus stewardship" has been emphasised.[26]

The message from the Periodic Table projections of planetary boundaries and environmental science is clear. Changes in approach are needed that must involve better husbanding of the critical elements, focusing on conserving and recycling available supplies of the rare ones and finding new substitutes for specific applications, where possible.[27] The changes must also involve finding ways to reduce the use of more abundant elements to a minimum, while much more consideration must be given to the entire cycle of use, repair, upgrading, repurposing, by-products, waste and disposal, in order to prevent damage to the planetary environment. Manufacturers might consider emulating Apple's 2017 pledge to make its smartphones entirely from recycled material.[28] Inspiration may be taken from the decision[29] by the Tokyo Organising Committee of the Olympic and Paralympic Games to manufacture the approximately 5,000 gold, silver and bronze medals for use at Tokyo 2020 only from consumer electronics such as used mobile phones, after recycled metals were used to produce medals for the 2012 London Games and the 2016 Rio de Janeiro Games.

Recycling and re-use of available element stocks must be an essential approach to consider – but while human creativity and ingenuity will undoubtedly improve capacities to achieve this, it will not always be technically or economically feasible and, when it is, it will require major revision of many industrial processes and production models. Consequently, the limited planetary stock of some elements may ultimately become widely dispersed in non-recoverable forms. A "systems thinking" approach is vital,[30] in which considerations of science, technology, economics and environmental impact are integrated into a holistic view.

Ensuring the sustainable development of the planet requires that we urgently learn how to be better stewards of the Earth's limited stock of the elemental building blocks inventoried in the Periodic Table We need to improve our capacities to husband them, using them with greater efficiency, with attention to conserving stocks and supplies and with increased awareness of the adverse consequences of how we exploit them. As the science of atoms and molecules and the inheritor of Mendeleev's Periodic Table chemistry is central to making this better stewardship possible.

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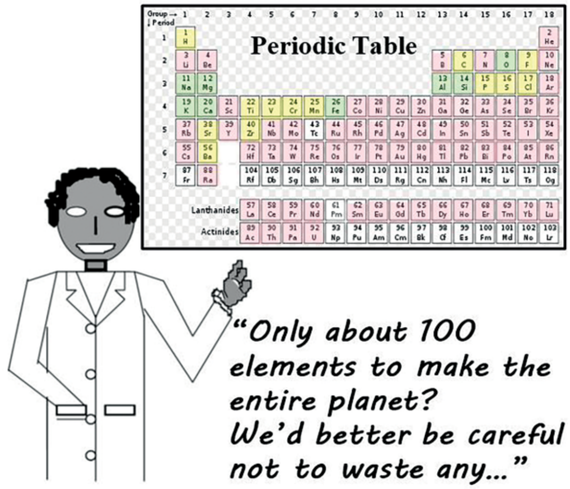

The 150th anniversary of Mendeleev's Periodic Table celebrates his success in systematically organising the known elements and predicting the existence of new ones. It is also an opportunity to remember that there are less than 100 stable elements on our planet and from the finite stocks of these we must derive all the materials that are required for life, well-being and comfortable living.

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