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Chemistry must respond to the crisis of transgression of planetary boundaries

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Recent assessments alarmingly indicate that many of the world's leading chemicals are transgressing one or more of the nine planetary boundaries, which define safe operating spaces within which humanity can continue to develop and thrive for generations to come. The unfolding crisis cannot be ignored and there is a once-in-a-century opportunity for chemistry – the science of transformation of matter – to make a critical difference to the future of people and planet. How can chemists contribute to meeting these challenges and restore stability and strengthen resilience to the planetary system that humanity needs for its survival? To respond to the wake-up call, three crucial steps are outlined: (1) urgently working to understand the nature of the looming threats, from a chemistry perspective; (2) harnessing the ingenuity and innovation that are central to the practice of chemistry to develop sustainable solutions; and (3) transforming chemistry itself, in education, research and industry, to re-position it as 'chemistry for sustainability' and lead the stewardship of the world's chemical resources. This will require conservation of material stocks in forms that remain available for use, through attention to circularity, as well as strengthening engagement in systems-based approaches to designing chemistry research and processes informed by convergent working with many other disciplines.

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Introduction

Chemistry's extraordinary success as the science of transformation of matter, bringing huge benefits to humanity, has been central to the expanding quantity and diversity of artefacts generated by human beings. The production of anthropogenic mass (global total dry mass of material contained in inanimate solid objects made by humanity) doubled every 20 years since 1900, in 2020 reaching 30Gt per year and totalling c. 1.1 trillion tonnes present on the planet.¹ This accumulated amount equalled the dry weight of total biomass on Earth for the first time and, on current trends, total anthropogenic mass will be triple the dry weight of biomass by 2040. Concomitantly, the global chemical industry's production capacity (excluding pharmaceuticals) almost doubled between 2000 and 2017, from about 1.2 to 2.3 billion tonnes.²

However, there has been mounting environmental cost, including degradation of global habitat quality and loss of planetary ecosystem stability. Global atmospheric CO₂ concentrations reached their highest historic level of 421.37 ppm in May 2022. They are likely to drive global warming since pre-industrial times above the 1.5 °C safe limit in the 2020s.³ At the same time, the majority of the 500 main chemicals on the market have been judged unsustainable in terms of their environmental impact.⁴

This is a wake-up call for all humanity to attend to the unfolding crisis. That it is not the first alarm heightens the urgency of now paying attention. Coining the term Anthropocene recognized that a transition was in rapid progress to a new period in which humanity has become the dominant force shaping the planet's environment.⁵ Harbingers of this transition⁶ were seen in writings on the vulnerability of 'spaceship Earth',⁷ the environment⁸ and the limits to growth.⁹ The 1987 World Commission on Environment and Development¹⁰ advanced the concept of sustainable development, a key step towards the UN Sustainable Development Goals (SDGs) agreed in 2015.¹¹

As well as setting the SDGs, other global responses have included a range of efforts by the UN Environment Programme¹² and Committee of the Parties (COP) negotiations of the UN Framework Convention on Climate Change.¹³ In all of these, roles for science and technology have been highlighted,¹⁴ the need for chemistry recognised and attention drawn to the

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mapping of SDGs directly into chemistry.¹⁵ Academia and industry have increasingly devoted attention to important aspects of the challenges,¹⁶ marked by developments including environmental chemistry since the 1950s and green chemistry which started to become prominent in the 1990s, as well as sustainable, one-world and circular chemistry. But much greater effort is now needed¹⁷ and chemistry needs to respond urgently and effectively across all branches of education, research and practice, with industry having centrally important roles.

How can chemists contribute to meeting these challenges and restore stability and resilience to the planetary system that humanity needs for its survival? To respond to the renewed and intensified ringing of alarms, and to develop the concept and apply the approach of chemistry for sustainability,¹⁸ three crucial steps are outlined in this article: (1) urgently working to understand the nature of the threats, from a chemistry perspective; (2) harnessing the ingenuity and innovation that are central to the practice of chemistry to develop sustainable solutions; and (3) transforming chemistry itself, in education, research and practice, to re-position it as a sustainability science and strengthen its capacities to work, in concert with

other disciplines, on long-term approaches that will avoid unsustainable practices in the future.

Understanding the problem

The planetary boundaries approach, developed in 2009–2015,¹⁹ identified nine aspects of anthropogenic threats to critical Earth systems, for each of which ‘safe operating spaces’ needed to be defined. For seven of these boundaries, control variables were proposed and threshold levels set for the safe operating limits. In many cases, the control variables chosen as indicators were chemical entities (Table 1), including the biogeochemical flows of carbon, nitrogen and phosphorus which are major contributors to currently accelerating planetary changes. The category of novel entities (including synthetic chemicals, micro-particulate materials and other new types of engineered materials or organisms not previously known to the Earth system) is one of two planetary boundaries not yet officially quantified, owing to the difficulty of choosing control variables.

The handful of chemicals initially selected as signals of the planetary condition represent only the tip of a vast iceberg of materials that need to be considered. Around 200 million

Table 1 Planetary boundaries and their chemical control variables at 2015

		Planetary boundary Threshold				Important opportunities for chemistry contributions
Variable:	Indicator measured	Below boundary (safe)	In zone of uncertainty (increasing risk)	Beyond zone of uncertainty (high risk)	Boundary not yet quantified globally	
Atmospheric aerosol loading:	Aerosol Optical Depth (AOD), but much regional variation					Better understanding of formation of atmospheric aerosols as suspensions of liquid, solid, or mixed particles; and of processes to prevent them
Biogeochemical flows:	Nitrogen: industrial & intentional biological fixation	62 Tg/yr		152 Tg/yr		Sustainable synthesis and applications of NH ₃
	Phosphorus: flow from freshwater systems into ocean	11 Tg/yr		22 Tg/yr		Sustainable synthesis and applications of P compounds
Change in biosphere integrity:	Genetic diversity (extinction rate)	<10 E/MSY		100–1,000 E/MSY		
	Functional diversity (Biodiversity Intactness Index)			(E/MSY: extinctions per million species-years)		
Climate change:	Atmospheric CO ₂ concentration	350 ppm		398.5 ppm in 2015 (rose to 412.5 ppm in 2020)		Reduction of CO ₂ production/elimination of atmospheric release. Prevention of atmospheric release of CH ₄ , N ₂ O, NO _x , C-F gases
	Energy imbalance at top of atmosphere (radiative forcing)	1.0 W m ⁻²		2.3 W m ⁻²		
Freshwater use	Maximum amount of consumptive blue water use (km ³ yr ⁻¹)	4000 km ³ yr ⁻¹		2,600 km ³ yr ⁻¹		Development of new, low-cost, sustainable processes for water purification
Land-system change	Area of forested land as % of original forest cover	75 %		62 %		
Novel entities in environment:	[Chemical pollution] renamed: ‘Novel entities’ – not yet defined					Application of sustainability principles, systems thinking, environmental impact assessments to ensure
Ocean acidification	CO ₃ ²⁻ concentration, average global surface ocean saturation state with respect to aragonite	≥80 % PIA		84 % PIA (PIA = % of pre-industrial aragonite saturation state of mean surface ocean)		Reduction of CO ₂ production/elimination of atmospheric release.
Stratospheric ozone depletion:	Stratospheric O ₃ concentration, Dobson Units (DU)	<5% rpi		Variable (rpi: % reduction from preindustrial level of 290 DU, assessed by latitude)		Ceasing all use of CFCs, HFAs, HCFCs. Prevention of atmospheric release of N ₂ O, NO _x .



discrete chemical entities are known and the number grows at around 10 million per year. Many of these substances have only ever been prepared in sub-gram quantities, but over 350 000 chemicals have been registered for production and use, either as single entities or in a vast array of combination materials. Among ubiquitous devices, the smartphone typically contains at least 30 elements in an individual handset and different models of smartphones incorporate more than 70 of the periodic table's members, either in the elemental form or as compounds or mixtures.²⁰ As well as the issue of depletion of useable elemental reserves, the impacts on the environment of these substances, when produced at large scale, remain largely unknown. The United Nations Environment Programme (UNEP) 2019 report, *Global Chemicals Outlook II*, showed that the commitment countries had made in 2002 at the World Summit on Sustainable Development, to minimize by 2020 the adverse effects of chemicals and pollutants passing into the environment, was not being achieved.²

Solutions to the challenges to sustainability presented by large-scale manufacturing are evolving – but this is still work in progress. The ‘throwaway’ society popularised in the 1950s–1960s was countered by growing concerns about over-consumption and environmental damage which led to a movement to ‘reduce, reuse and recycle’ (the ‘3Rs’). This alternative to the linear ‘take-make-dispose’ model has informed circular economy, waste reduction and sustainable consumption and production (‘living lightly’) policies in many countries.²¹

Two recent publications signal the urgency for chemistry to take action. One concerns the nature of the previously ill-defined planetary boundary related to ‘novel entities’. A measure of the production and release of plastics has been proposed as one possible parameter for this boundary, and the case presented that the safe operating space of the novel entities planetary boundary has already been transgressed.²² The other report⁴ has considered what planetary metrics are of relevance for the absolute environmental sustainability assessment of chemicals. Nearly 500 chemicals were assessed in relation to seven planetary boundaries and most were found to transgress at least one of the thresholds for their safe operating limits. The study has highlighted the need to incorporate absolute environmental sustainability criteria into environmental assessments for all chemical entities produced at large scale, to aid researchers and industries in the quest for sustainability.

Chemistry for sustainable solutions

Sustainability science has developed a number of key insights relevant to all disciplines that seek to contribute to sustainable development. One principle is that sustainability is a property that emerges from the operation of an entire system and not simply attributable to isolated components. Thus, a product cannot be said to be ‘sustainable’ solely because it is derived from a renewable source, because its manufacturing process is based on green chemistry principles, or because it is recycled in some way after primary use, if it continues to be used in a manner or at a scale that transgresses planetary boundaries and damages Earth systems. It is now imperative that chemists

developing new products or processes that will operate at manufacturing scale consider the potential environmental costs and impacts – not only for the core reactions or processes, but also for the entire chain of events from sourcing input materials and energy to the disposal of all by-products, wastes and the articles themselves at the end of the primary use. The consideration needs to include the entire gamut of short-to-long-term effects on all parts of the planetary environment, and to be concerned with the depletion of natural resources where these may become limiting – but even for the most abundant or renewable natural resources it needs to be concerned with how global scale-up and turnover of biogeochemical flows and the dispersal of materials across the planet may impact on these diverse aspects of the environment. While riding their hobby horses in pursuit of creative instinct or commercial interest, it is vital that chemistry practitioners carry out due diligence with regard to these considerations. All stages of supply, manufacturing, application and disposal need to be regarded using systems principles and tools. These are embedded in green, sustainable and circular chemistry, with quantifications derived from life cycle analysis, planetary boundaries and absolute environmental sustainability criteria. This totality of assessment provides the basis for overall judgement about sustainability as well as for the concept and approach encapsulated in ‘chemistry for sustainability’.¹⁸

New reaction processes

Among the new and re-merging innovations currently receiving attention, those focusing on the sustainability of reaction processes, including the use of non-hazardous materials and conditions and applications of green solvents,²³ will be of particular interest to synthetic chemists. The search for more environmentally benign processes for chemical reactions has branched into a number of directions in recent years. For the choice of reaction medium, at least three avenues have been under development. One is the identification of novel solvents, including ionic liquids, that offer economic and environmental advantages as well as chemical benefits.²⁴ A second direction is the application of flow chemistry processes.²⁵ The traditional approach to batch-wise chemical reactions in non-aqueous solvents presents many challenges in relation to the fate of solvents and the material and energy demands of synthesis, work-up and purification processes. Third, developments are advancing ‘solventless’ and ‘reagentless’ chemistry, including resurgent interest in mechanochemistry, microwave processes, sonochemistry, and visible light/sunlight redox reactions.²⁶ In the search for reactions that are speedy, efficient and take place under mild conditions, with high stereo- and enantio-specificity, much chemical ingenuity has been invested in catalyst design.²⁷

Benign by design

Beyond cleaner processes, sustainability requires paying much more attention to products that are ‘benign by design’ at all stages.²⁸ An illustration can be seen in the case of ammonia, traditionally manufactured by the Haber–Bosch process which



sources hydrogen by cracking CH_4 , as well as using energy to drive the reaction that is usually sourced from fossil fuels, together contributing massively to atmospheric release of CO_2 . While there are now major efforts²⁹ to manufacture 'green' NH_3 , these need to be accompanied by great reduction in the excessive biogeochemical flow of nitrogen (Table 1). Other challenges for chemists include sustainable energy production from renewable, sustainable, non-polluting sources,³⁰ including design of compounds that can mediate the transformation of solar energy to electricity,³¹ and capture of CO_2 at the site of production³² as well as *via* atmospheric sequestration, combined with designing alternative fates for CO_2 ,³³ and developing sustainable alternatives to traditional concrete³⁴ and reuse of waste concrete.³⁵ Achieving goals for reductions in CO_2 emissions requires analytical measurements and monitoring, integrated into comprehensive life cycle assessments, while design of alternative fates for CO_2 must ensure that the carbon remains 'locked up' for long time periods and is not just briefly delayed on its journey back into the atmosphere.³⁶ As noted by Artz *et al.*,³⁷ this point requires a more nuanced approach to taking CO_2 utilization as a measure for global CO_2 mitigation, and the use of CO_2 as feedstock for chemicals should be analysed as a route towards "de-fossilization", rather than as a technology for CO_2 mitigation.

Circularity and the post-trash age

For chemists, imprints of the circular economy³⁸ concept have been seen in 'green chemistry'.³⁹ With origins based in evolving industrial and academic movements, the term was defined and fleshed out as a set of 12 principles by Anastas and Warner.⁴⁰ Green chemistry has had major impact, reorienting chemistry education, research and practice towards sustainability objectives.^{39a,41} Sustainable chemistry has many features in common with green chemistry, while emphasizing broader concerns with ecology, service and function and incorporating systems tools and transdisciplinary approaches.⁴² Similar principles are also seen in the more recent emergence of 'circular' chemistry⁴³ which extended the 3Rs to 11Rs, transitioning to restorative and regenerative design principles for resource efficiency, utility and maintenance of high value when feasible.⁴⁴ The concept of 'one-world' chemistry, which recognises the interconnectedness of the health of human beings, animals and the environment, adopts systems thinking and cross-disciplinary working to understand and navigate the interfaces between science, the environment and society and underscore chemistry's central position in providing the molecular basis of sustainability.^{15b,45} Embedded in all these concepts is the recognition that a new understanding is required of what has traditionally been termed 'waste' – the 'unwanted' materials that did not become incorporated into the intended product, as well as the product itself after its primary use. The World Bank estimated⁴⁶ in 2018 that global generation of solid waste exceeded 2 billion tonnes per year and will rise by 70 per cent by 2050. The new understanding in the 'post-trash' age⁴⁷ sees all the material outputs as resources for conservation and further reuse. This is especially critical when a process goes to scale and will determine whether

it can deliver bulk and platform chemicals as well as large-volume speciality chemicals in a sustainable manner, with minimal environmental footprint and predictable re-uptake at the 'end of life' of the product. Achieving a post-trash society⁴⁷ requires⁴⁸ synergies at the interface of science, society and policy. The recent demonstration of computer-designed repurposing of waste to drugs⁴⁹ signposts the directions of waste-to-valuable-resource reincarnation and circularity along which chemistry for sustainability should operate.

Leveraging the digital transformation

Increasing use of the rapidly evolving digital tools and platforms, including big data handling, machine learning and artificial intelligence applications as well as robotics, is enabling chemists to make fundamental changes in their approach to sustainability challenges at all stages of the chemistry enterprise, including in Industry 4.0.⁵⁰ These range from the scoping of the chemical space, which can rapidly identify large numbers of close analogues of any molecule to expand the chemical diversity of products under consideration,⁵¹ the prediction of chemical properties and design of optimum chemical pathways for production, including streamlining chemical explorations by application of machine learning to chemical reactivity,⁵² to the scoping of potentials for circularity options for recovery, reuse and recycling and the anticipation of likely environmental fates and ecological impacts of different pathways of sourcing, production, use and disposal. Across the spectrum, the chemist will be seeking to apply orientations that reduce the number of reaction steps, increase efficiency and recovery and minimise overall environmental impact, including reducing biogeochemical flows.

Realigning chemistry and chemical industry for a sustainable world

The emergence of the 'triple bottom line' in business in the early 1990s added environmental and social concerns to the perennial focus on economics. While this extended the scope of business to include considerations of planet and people as well as profit, it is evident that a rebalancing among this trio of factors is now essential, with much greater priority being given to the planet component encompassing environmental protection and sustainability.⁵³ The vital and urgent contributions needed from chemistry in response to the unfolding planetary boundaries crisis cannot simply happen within a 'business as usual' framework, and the present decade's worldwide political agreement on climate and sustainable development goals provides a narrow window of opportunity to avert catastrophic, long-term changes to planetary systems.^{14b} A dual-track response is required in which industry solutions that can be rapidly advanced and scaled up are given immediate support while, for the longer term, fundamental, systemic changes are progressively embedded to reorient the discipline as a leading sustainability science. These must reshape the way chemists approach all aspects of their work in education, research and industry.^{15b,c} It is essential to recognize that these three



constituents have complementary roles, as demonstrated by the constructive ways that both academia and industry already serve as the sources and mediators of knowledge, processes and products and as contributors and observers in global policy processes within international bodies.

For industry, critical areas for attention will follow principles of decarbonising the economy and energy in general, including, for the chemical industry, decarbonising steps in manufacturing/synthesis, and cutting all process- and product-related environmental emissions.⁵⁴ This entails paying attention to the sustainable sourcing of materials, green chemistry principles of manufacturing and in-built design to maximise material circularity. As an example, a German Chemical Industry Association study⁵⁵ highlighted that achieving full greenhouse gas neutrality by 2050 will require heavy R&D investment in new process technologies for basic chemicals, and improved mechanical and chemical recycling processes, backed by a suitable policy framework and regulations. Replacement of fossil fuels as energy sources will necessitate developing processes to use electrons directly or *via* carriers such as hydrogen.

The science–society–policy interface is of critical importance in ensuring the real-world practicality of expectations for industry in relation to sustainability goals. In recent decades, there has been an increasing tendency for manufacturing and R&D operations to move to countries where they can be conducted at lower costs, where they may be subject to lower standards of environmental regulations and less rigorous compliance oversight. Rebalancing among the trio of factors in the triple bottom line can only be viable economically if there is a level playing field of regulatory factors. This requires global agreements on international standards for good manufacturing practice and environmental impacts. Combined efforts from UNEP, the World Trade Organization and the United Nations Conference on Trade and Development will be needed, with concerted inputs from chemistry and chemical industry through professional bodies and industry organizations. As well as the COP and SDG processes, the Montreal Protocol, finalised as an international treaty in 1987 and the Political Declaration and Implementation Plan adopted at the 2002 World Summit on Sustainable Development provide examples where the combined forces of science, industry, social demand and political policy have been focused on reaching agreement to achieve major environmental goals.^{2,56}

Here we present three examples that are representative of different kinds of problems, to explore the implications for the discipline and profession of chemistry.

New platforms for organic chemicals

Since the 19th century, chemists have become accustomed to regarding hydrocarbon-related compounds as the main source of starting materials for synthesis. This has strongly influenced all aspects of chemistry: industry has come to depend on petroleum and natural gas for its feedstocks, with simple olefins, aromatics and their derivatives being among the largest-volume products manufactured;⁵⁷ researchers have demonstrated their skill and ingenuity by developing processes

for cracking, metathesising and functionalising hydrocarbons; and chemistry curricula and textbooks have traditionally reflected a mindset in which syntheses generally follow pathways of increasing functionalisation/oxidation from hydrocarbon precursors.

Ending the use of fossil hydrocarbons as fuels will eliminate one of the main drivers of climate change. In the short term, this will extend the availability of hydrocarbon raw materials for synthesis. However, in the longer term, chemistry must switch to renewably-sourced feedstocks for the ever-expanding range and scale of organic compounds required. The biological products of metabolism are the most likely source – and these are, overwhelmingly, highly oxidised compounds such as cellulose and lignin that require depolymerisation to serve as versatile feedstocks,⁵⁸ as well as a host of other bio-molecules incorporating important features such as chiral centres and multiple functionalities. Implications for industry include the need to source bio-organic materials, not only cheaply and efficiently but in ways that do not compete with other critical areas such as natural habitats, food production and clean water, do not liberate environmentally-damaging wastes during transformations into products or subsequent use and disposal, but do offer practical avenues for material recovery, reuse or recycling in cyclical systems. The long-standing concept of ‘chemurgy’ (use of agriculture as source of chemical feedstocks) must now be revisited and revived, modernising the approach and bringing it into alignment with current understanding of sustainability principles and practices.⁵⁹ A challenge for chemistry researchers is to switch from seeking regio- and stereo-selective oxidative processes for hydrocarbon functionalization to devising site-specific reduction and substitution reactions of highly functionalised backbones found in many biomolecules, while utilizing green, sustainable and circular chemistry principles and information on environmental requirements and impacts to guide the choices of reagents, solvents and conditions. Future chemistry graduates will need to be equipped with the knowledge and skills to take forward these industry and research ambitions, implying not only revised chemistry curricula, but also that competence is developed in systems thinking and cross-disciplinary working.

Sustainability of plastics

Due to their ease of production, versatility and low cost, plastics emerged during the 20th century as among the most ubiquitous and widely used materials manufactured on the planet – but with the majority of all the plastic ever made ending up in landfill sites or scattered in the environment.⁶⁰ Deep concern about the multiple environmental impacts of plastics²² has been reflected in the passage of a historic resolution in the UN Environment Assembly, to forge an international legally binding agreement by 2024 that addresses the full life-cycle of plastics, the design of reusable and recyclable products and materials, and the need for enhanced international collaboration to facilitate access to technology, capacity building and scientific and technical cooperation.⁶¹ The challenge, “not only multidisciplinary but also inter- and transdisciplinary research



with integrated and multifaceted approaches are needed to produce novel eco-friendly materials with features similar to those of traditional plastics, as well as with acceptable economic and environmental impact”, is clearly framed in a way that speaks to chemists. They will need to tailor their responses in ways that take account of the multiplicity of plastics for diverse applications, involving a broad range of chemical structures and functional groups. Redesign of plastics will be necessary, to supply a wide and growing range of applications while inventing novel structures that meet the new, urgent requirements for sustainability across the entire spectrum, from sourcing of monomers, through synthesis and uses, to return and further use. For short-term approaches, research has opened promising avenues related to the sourcing of suitable monomers from microorganisms and plants, the production of biodegradable and recyclable polymers with useful properties and the development of methods for the recovery of monomers at the end of the useful life of the material. The challenge for chemistry is a multi-faceted one, as illustrated by the case of microplastics (particles < 5 mm in size). These are either used as small beads in many applications in cleaning and cosmetics, or result from physical degradation of macroplastic products. They have become ubiquitous in the environment, even in deep-ocean and polar regions (microplastics have now been observed⁶² in fresh snow in the Antarctic), and have been identified as a major threat to ecological niches such as coral as well as to overall environmental stability. Chemists need to take a comprehensive, Earth-system approach to the design, production and fate of plastics to eliminate this environmental hazard, including through attention to biodegradation,⁶³ recapture and reuse/recycling of plastic materials in green chemistry and circular processes, including strategies and processes for depolymerization.⁶⁴

Element stewardship

Every element in the periodic table with a stable isotope (as well as some radioactive ones) finds commercial applications⁶⁵ and the number and diversity of these uses is continuously mushrooming. Moreover, of more than 60 elements that can be detected in at least trace amounts in the human body, at least 28 are thought to be required for aspects of human metabolism and most of the elements are utilized in pharmaceuticals and other medical products.⁶⁶ Situated at the confluence of these manufacturing and health interests, chemistry's capacities to analyse, synthesise and design materials, complemented by increasing understanding about the interactions between chemicals and the environment, now define an emerging, critical role for chemistry: to be a leader in the stewardship of the planet's element resources. EuChemS has made important contributions to this objective through its work to highlight element scarcity and to engage on this issue at the science-policy interface.⁶⁷

For a number of elements, low abundance levels and/or very restricted distribution of favourable extraction sites, combined with high importance in large-scale uses, has led to a focus on their 'strategic', 'critical' or 'endangered' character.⁶⁸ Among prominent examples, lithium is receiving increasing attention

due to its importance in batteries, making it a critical element for the global energy transition to electric-powered vehicles. With pressure on supplies from the known main sources, which are located in only a few countries (especially Argentina, Australia, Bolivia, Chile, China, and USA) and with a low substitutability at present, heightened attention is being given to new sources (including seawater) and Li substitutes, for example, batteries based on other metals such as Al, Au, Fe, Mg, Na, Zn.⁶⁹ There is an urgent need to solve the battery problem for storing energy sustainably as the world moves towards decarbonised energy supplies. This example shows how element stewardship has multi-sectoral ramifications, ranging from policies to ensure access, as a strategic national, regional or geopolitical issue, to science and technology challenges linked with the efficiencies of extraction, use, recovery and recycling of available supplies and with the continual need to identify practical alternative materials to build resilience⁷⁰ to threatened supply shortages.

For other, more highly abundant materials, elements stewardship must especially focus on concerns about the overall biogeochemical flows of anthropogenic materials and ways to recycle materials or return them to the environment with the least possible harm. The implications of chemistry principles that have long been the bedrock of the discipline – including that matter cannot be created or destroyed, but only transformed; and that entropy favours the increasing dispersal of both matter and energy – need to be understood also at a planetary scale. The dilution and dispersal of elements at large scale is both a waste of finite resources and a threat to the environment that supports all life on the planet, yet the avoidance of this waste also consumes energy and resources.

Messages for the chemistry community

There have been alarms in the past, alerting the world to the growing dangers of increasing resource utilization, matter transformation and lack of attention to waste in all its forms, but these rarely resulted in effective action. This would have required major disruptions to economies and uncomfortable changes to patterns of personal, social and political behaviour. However, the latest alarm call, signalled by transgression of planetary boundaries and evidence that we are already at the brink of catastrophic long-term changes to Earth systems, is louder and more urgent. That the transgression of planetary boundaries is, in many cases, intimately connected with biogeochemical flows, makes the call of particular relevance to the profession of chemistry, which needs to contribute to practical technical solutions as well as carrying and amplifying the message at the science/society/policy interface. Fortunately, chemistry now has a better understanding of sustainability and more tools than ever with which to help achieve sustainable solutions – but it will need to undergo deep-seated changes, as highlighted here, to make the needed contributions.

Chemistry is vitally important for understanding and managing Earth's material and biogeochemical flows. Both conceptual and strategic shifts are needed in the design principles and planning of chemical transformations. These shifts necessitate extending the sphere of chemistry's concern beyond



the conversion of resource to target, by adding the requirement that all material outputs will be further utilised, either by conversion to a new serviceable resource or by return to the cradle. Exemplifying the principles of circularity, the shifts must aim to maintain the utilitarian value of chemical matter for as long as possible. Beyond the issue of conservation of useful material, the conceptual and strategic shifts must also provide the bridge between chemistry and the critical determinants of sustainability and stability of Earth systems encapsulated in the planetary boundaries framework.

Stewardship of the planet's chemical resources is fundamental to efforts to reduce and, in future, prevent the transgression of planetary boundaries that presently threatens the stability of Earth systems on which all societies depend. The implications for chemistry involve reorientation of all aspects of the discipline and profession. In education, this includes a redirection of content towards green and sustainable chemistry,^{35,45a} coupled with the development of knowledge and competencies related to systems thinking, convergence working and biogeochemistry principles. In research, it includes awareness of the planetary boundaries and planetary impacts of biogeochemical flows, as well as the honing of skills in cross-disciplinary working and systems-based approaches. In industry, it includes a commitment to incorporate comprehensively the tools available, such as life-cycle assessments, circular material flow and absolute environmental sustainability criteria, into the development of processes and products that are benign and circular by design and avoid transgression of planetary boundaries.

Author contributions

Conceptualization, S. A. M., S. E. C., A. K., H. H. and G. M.; investigation, S. A. M., S. E. C., A. K., H. H. and G. M.; project administration, S. A. M.; writing – original draft, S. A. M.; writing – review & editing, S. A. M., S. E. C., A. K., H. H. and G. M.

Conflicts of interest

There are no conflicts to declare.

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References

- 1 E. Elhacham, L. Ben-Uri, J. Grozovski, Y. M. Bar-On and R. Milo, *Nature*, 2020, **588**, 442–444, DOI: [10.1038/s41586-020-3010-5](https://doi.org/10.1038/s41586-020-3010-5).
- 2 *Global Chemicals Outlook II*, ed. A. Halpaap and J. Dittkrist, United Nations Environment Programme, Nairobi, 2019, Available at: <https://wedocs.unep.org/bitstream/handle/20.500.11822/28113/GCOII.pdf>.
- 3 (a) *Global CO₂ emissions rebounded to their highest level in history in 2021*. UN Climate Change, 9 March 2022, Available at: <https://unfccc.int/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021>; (b) WMO, *Global Annual to Decadal Climate Update for 2022–2026*, World Meteorological Organization, Geneva, 2022, Available at: https://hadleyserver.metoffice.gov.uk/wmolc/WMO_GADCU_2022-2026.pdf.
- 4 (a) V. Tulus, J. Pérez-Ramírez and G. Guillén-Gosálbez, *Green Chem.*, 2021, **3**, 9881–9893, DOI: [10.1039/d1gc02623b](https://doi.org/10.1039/d1gc02623b); (b) N. Cotterrell, *Chem. World*, 9 December 2021, <https://www.chemistryworld.com/news/majority-of-top-chemicals-on-market-deemed-environmentally-unsustainable-by-new-metric/4014878.article>.
- 5 (a) L. J. Issberner and P. Léna, *Anthropocene: the vital challenges of a scientific debate*. UNESCO Courier, 2018-2, Available at: <https://en.unesco.org/courier/2018-2/anthropocene-vital-challenges-scientific-debate>; (b) World Commission on Environment and Development, *Our Common Future*, United Nations, New York, 1987, <https://digitallibrary.un.org/record/139811?ln=en>; (c) *The Sustainable Development Goals*, United Nations, New York, 2015, <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>.
- 6 A. Rome, *Nature*, 2015, **527**, 443–445, DOI: [10.1038/527443a](https://doi.org/10.1038/527443a).
- 7 (a) K. E. Boulding, *The Economics of the Coming Spaceship Earth*, in *Environmental Quality in a Growing Economy*, ed. H. Jarrett, Oxford University Press, London, 1966, pp. 3–14, <https://web.archive.org/web/20060927091611/http://dieoff.org/page160.htm>; (b) R. Buckminster Fuller, *Operating Manual for Spaceship Earth*, Southern Illinois University Press, Carbondale, 1969, <https://web.archive.org/web/20100717141812/http://bfi.org/about-bucky/resources/books/operating-manual-spaceship-earth>.
- 8 (a) B. Commoner, *Nature, Man, and Technology*, Alfred A. Knopf, New York, 1971; (b) B. Ward and R. Dubos, *Only One Earth: The Care and Maintenance of a Small Planet*, W. W. Norton, New York, 1972.
- 9 D. H. Meadows, D. Meadows, J. Randers and W. W. Behrens, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, Universe Books, Eugene OR, 1972, <https://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf>.
- 10 World Commission on Environment and Development, *Our Common Future*, United Nations, New York, 1987, <https://digitallibrary.un.org/record/139811?ln=en>.
- 11 (a) *Transforming our world: the 2030 Agenda for Sustainable Development*. Resolution adopted by the General Assembly on 25 September 2015, Document A/RES/70/1, United Nations, New York, 21 October 2015, https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E; (b) *The Sustainable Development Goals*, United Nations, New York, 2015, <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>.
- 12 *Planetary Action*, UN Environment Programme, Nairobi, 2021, <https://www.unep.org/annualreport/2021/index.php>.



- 13 COP26 Outcomes, *UN Climate Change Conference*, Glasgow, 2021, <https://ukcop26.org/the-conference/cop26-outcomes/>.
- 14 (a) *Science Technology and Innovation for SDGs Roadmaps. United Nations Interagency Task Team on Science Technology and Innovation for the SDGs, IATT Background Paper*, June 2018, https://sustainabledevelopment.un.org/content/documents/19009STI_Roadmap_Background_Paper_pre-STI_Forum_Final_Draft.pdf; (b) *Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future. Intergovernmental Panel on Climate Change*, Press Release, Geneva, 2022/08/PR, 28 February 2022, Available at: https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_PressRelease-English.pdf.
- 15 (a) S. A. Matlin, G. Mehta, H. Hopf and A. Krief, *Nat. Chem.*, 2015, 7, 941–943, DOI: [10.1038/nchem.2389](https://doi.org/10.1038/nchem.2389); (b) S. A. Matlin, G. Mehta, H. Hopf and A. Krief, *Nat. Chem.*, 2016, 8, 393–396, DOI: [10.1038/nchem.2498](https://doi.org/10.1038/nchem.2498); (c) A. M. Noce, *Chem. Eng. News*, 2018, 96(22), 43. <https://pubs.acs.org/doi/10.1021/cen-09622-comment>; (d) D. Cole-Hamilton, *Chem.–Eur. J.*, 2020, 26, 1894–1899, DOI: [10.1002/chem.201905748](https://doi.org/10.1002/chem.201905748).
- 16 J. Rockström, X. Bai and B. DeVries, *Global Sustainability*, 2018, 1, E6, DOI: [10.1017/sus.2018.8](https://doi.org/10.1017/sus.2018.8).
- 17 *Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future. Intergovernmental Panel on Climate Change*, Press Release 2022/08/PR, Geneva, 28 February 2022, https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_PressRelease-English.pdf.
- 18 (a) P. G. Mahaffy, S. A. Matlin, M. Potgieter, B. Saha, A. Visa, S. Cornell, F. Ho, V. Talanquer, J. Wissinger and V. Zuin, *Chem. Internat.*, 2021, 43(4), 6–10, DOI: [10.1515/ci-2021-0402](https://doi.org/10.1515/ci-2021-0402); (b) P. Anastas, B. Han, W. Leitner and M. Poliakoff, *Green Chem.*, 2016, 18, 12, DOI: [10.1039/c5gc90067k](https://doi.org/10.1039/c5gc90067k).
- 19 (a) J. Rockström, W. Steffen, K. Noone, *et al.*, *Nature*, 2009, 461, 472–475, DOI: [10.1038/461472a](https://doi.org/10.1038/461472a); (b) W. Steffen, K. Richardson, J. Rockström, *et al.*, *Science*, 2015, 347(6223), 736–747, DOI: [10.1126/science.1259855](https://doi.org/10.1126/science.1259855); (c) W. Steffen, W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig, *Anthropocene Rev.*, 2015, 2, 81–98, DOI: [10.1177/2053019614564785](https://doi.org/10.1177/2053019614564785).
- 20 B. Rohrig, *Smartphones: Smart chemistry, ACS ChemMatters Online*, April/May 2015, Available at: <https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/past-issues/archive-2014-2015/smartphones.html>.
- 21 (a) J. Kirchherr, D. Reike and M. Hekkert, *Resour., Conserv. Recycl.*, 2017, 127, 221–232, DOI: [10.1016/j.resconrec.2017.09.005](https://doi.org/10.1016/j.resconrec.2017.09.005); (b) S. Sakai, H. Yoshida, Y. Hirai, *et al.*, *J. Mater. Cycles Waste Manage.*, 2011, 13, 86–102, DOI: [10.1007/s10163-011-0009-x](https://doi.org/10.1007/s10163-011-0009-x); (c) M. Geissdoerfer, P. Savaget, N. M. P. Bocken and E. J. Hultink, *J. Cleaner Prod.*, 2017, 143, 757–768, DOI: [10.1016/j.jclepro.2016.12.048](https://doi.org/10.1016/j.jclepro.2016.12.048); (d) *State of the 3Rs in Asia and the Pacific. Regional 3R Forum in Asia and the Pacific, 9–12 April 2018, Indore, Madhya Pradesh, India. Secretariat of the Regional 3R Forum in Asia and the Pacific*, United Nations Centre for Regional Development (UNCRD), Nagoya, Japan, 2018, Available at: <https://www.uncrd.or.jp/content/documents/6781Final%20Indore%203R%20Declaration-11April%202018.pdf>; (e) *ABC of SCP. Clarifying concepts on sustainable consumption and production*, UN Environment Programme, Nairobi, 2010, Available at: https://www.scpclearinghouse.org/sites/default/files/10yfp-abc_of_scp-en.pdf.
- 22 L. Persson, B. M. C. Almroth, C. D. Collins, S. Cornell, C. A. de Wit, M. L. Diamond, P. Fantke, M. Hassellöv, M. MacLeod, M. W. Ryberg, P. S. Jørgensen, P. Villarrubia-Gómez, Z. Wang and M. Z. Hauschild, *Environ. Sci. Technol.*, 2022, 56, 1510–1521, DOI: [10.1021/acs.est.1c04158](https://doi.org/10.1021/acs.est.1c04158).
- 23 P. Dutta, A. McGranaghan, I. Keller, Y. Patil, N. Mulholland, V. Murudi, H. Prescher, A. Smith, N. Carson, C. Martin, P. Cox, D. Stierli, M. Boussemghoune, F. Barreteau, J. Cassayrec and E. Godineau, *Green Chem.*, 2022, 24, 3943–3956, DOI: [10.1039/d2gc00698g](https://doi.org/10.1039/d2gc00698g).
- 24 (a) D. D. Irge, *Am. J. Phys. Chem.*, 2016, 5(3), 74–79, DOI: [10.11648/j.ajpc.20160503.14](https://doi.org/10.11648/j.ajpc.20160503.14); (b) S. Koutsoukos, F. Philipp, F. Malaret and T. Welton, *Chem. Sci.*, 2021, 12, 6820–6843, DOI: [10.1039/d1sc01000j](https://doi.org/10.1039/d1sc01000j); (c) S. S. de Jesus and R. M. Filho, *Renew. Sustain. Energy Rev.*, 2022, 157, 112039, DOI: [10.1016/j.rser.2021.112039](https://doi.org/10.1016/j.rser.2021.112039).
- 25 (a) R. L. Hartman, *Curr. Opin. Chem. Eng.*, 2020, 29, 42–50, DOI: [10.1016/j.coche.2020.05.002](https://doi.org/10.1016/j.coche.2020.05.002); (b) M. B. Plutschack, B. Pieber, K. Gilmore and P. H. Seeberger, *Chem. Rev.*, 2017, 117, 11796–11893, DOI: [10.1021/acs.chemrev.7b00183](https://doi.org/10.1021/acs.chemrev.7b00183); (c) *Sustainable Flow Chemistry: Methods and Applications*, ed. L. Vaccaro, Wiley-VCH, Weinheim, 2017, ISBN: 978-3-527-33852-8, <https://www.wiley.com/en-us/Sustainable+Flow+Chemistry%3A+Methods+and+Applications-p-9783527338528>; (d) N. P. Tu, K. Sarris and S. W. Djuric, *RSC Adv.*, 2015, 5, 4754–4757, DOI: [10.1039/C4RA13931C](https://doi.org/10.1039/C4RA13931C).
- 26 (a) K. Tanaka and F. Toda, *Chem. Rev.*, 2000, 100, 1025–1074, DOI: [10.1021/cr940089p](https://doi.org/10.1021/cr940089p); (b) R. T. O'Neil and R. Boulatov, *Nat. Rev. Chem.*, 2021, 5, 148–167, DOI: [10.1038/s41570-020-00249-y](https://doi.org/10.1038/s41570-020-00249-y); (c) H. J. Kitchen, S. R. Vallance, J. L. Kennedy, N. Tapia-Ruiz, L. Carassiti, A. Harrison, A. G. Whittaker, T. D. Drysdale, T. D. S. W. Kingman and D. H. Gregory, *Chem. Rev.*, 2014, 114, 1170–1206, DOI: [10.1021/cr4002353](https://doi.org/10.1021/cr4002353); (d) G. Chatel, *Ultrason. Sonochem.*, 2018, 40, 117–122, DOI: [10.1016/j.ultsonch.2017.03.029](https://doi.org/10.1016/j.ultsonch.2017.03.029); (e) J. D. Bell and J. A. Murphy, *Chem. Soc. Rev.*, 2021, 50, 9540–9685, DOI: [10.1039/D1CS00311A](https://doi.org/10.1039/D1CS00311A).
- 27 (a) A. Kate, L. K. Sahu, J. Pandey, M. Mishra and P. K. Sharma, *Curr. Res. Green Sustainable Chem.*, 2022, 5, 100248, DOI: [10.1016/j.crgsc.2021.100248](https://doi.org/10.1016/j.crgsc.2021.100248); (b) R. A. Sheldon, I. Arends and U. Hanefeld, *Green Chemistry and Catalysis*, Wiley-VCH, Weinheim, 2007, ISBN: 3-527-30715-X.
- 28 D. Cespi, I. Esposito, R. Cucciniello and P. T. Anastas, *Curr. Res. Green Sustainable Chem.*, 2020, 3, 100028, DOI: [10.1016/j.crgsc.2020.100028](https://doi.org/10.1016/j.crgsc.2020.100028).
- 29 (a) C. Smith, A. K. Hill and L. Torrente-Murciano, *Energy Environ. Sci.*, 2020, 13, 331–344, DOI: [10.1039/C9EE02873K](https://doi.org/10.1039/C9EE02873K); (b) K. Han, J. Luo, J. Chen, B. Chen, L. Xu, Y. Feng, W. Tang and Z. L. Wang, *Microsyst. Nanoeng.*, 2021, 7, 7,



- DOI: [10.1038/s41378-020-00235-w](https://doi.org/10.1038/s41378-020-00235-w); (c) C. X. Huang, S. Y. Lv, C. Li, B. Peng, G. Li and L.-M. Yang, *Nano Res.*, 2022, **15**, 4039–4047, DOI: [10.1007/s12274-021-4009-4](https://doi.org/10.1007/s12274-021-4009-4); (d) P. Li, Z. Fang, Z. Jin and G. Yu, *Chem. Phys. Rev.*, 2021, **2**, 041305, DOI: [10.1063/5.0069736](https://doi.org/10.1063/5.0069736); (e) Y. Bicer and I. Dincer, *Int. J. Energy Res.*, 2017, **41**, 1987–2000, DOI: [10.1002/er.3756](https://doi.org/10.1002/er.3756); (f) M. A. Mushtaq, M. Arif, X. Fang, G. Yasin, W. Ye, M. Basharat, B. Zhou, S. Yang, S. Ji and D. Yan, *J. Mater. Chem. A*, 2021, **9**, 2742–2753, DOI: [10.1039/D0TA10620H](https://doi.org/10.1039/D0TA10620H); (g) S. Ghavam, M. Vahdati, I. A. G. Wilson and P. Styring, *Front. Energy Res.*, 2021, **9**, 580808, DOI: [10.3389/fenrg.2021.580808](https://doi.org/10.3389/fenrg.2021.580808); (h) H. D. Du, M. Chatti, R. Y. Hodgetts, P. V. Cherepanov, C. K. Nguyen, K. Matuszek, D. R. MacFarlane and A. N. Simonov, *Nature*, 2022, DOI: [10.1038/s41586-022-05108-y](https://doi.org/10.1038/s41586-022-05108-y).
- 30 (a) N. Carpenter, *Chemistry of Sustainable Energy*, Chapman and Hall/CRC, London, 2014, DOI: [10.1201/b1668](https://doi.org/10.1201/b1668); (b) R. Schlögl, *Top. Catal.*, 2016, **59**, 772–786, DOI: [10.1007/s11244-016-0551-9](https://doi.org/10.1007/s11244-016-0551-9).
- 31 (a) M. E. El-Khouly, E. El-Mohsnawy and S. Fukuzumi, *J. Photochem. Photobiol., C*, 2017, **31**, 36–83, DOI: [10.1016/j.jphotochemrev.2017.02.001](https://doi.org/10.1016/j.jphotochemrev.2017.02.001); (b) Z. Li, B. Li, X. Wu, S. A. Sheppard, S. Zhang, D. Gao, N. J. Long and Z. Zhu, *Science*, 2022, **376**(6591), 416–420, DOI: [10.1126/science.abm8566](https://doi.org/10.1126/science.abm8566); (c) H. J. T. Nkuisi, F. K. Konan, B. Hartiti and J. M. Ndjaka, in *Reliability and Ecological Aspects of Photovoltaic Modules*, ed. A. Gok, IntechOpen, London, 2020, ch. 7, Available at: <https://www.intechopen.com/chapters/68288>.
- 32 (a) *IPCC Special Report on Carbon Dioxide Capture and Storage. Working Group III of the Intergovernmental Panel on Climate Change*, ed. B. Metz, O. Davidson, H. C. de Coninck, M. Loos and L. A. Meyer, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2005, pp. 442, https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf; (b) S. Nanda, S. N. Reddy, S. K. Mitra and J. A. Kozinski, *Energy Sci. Eng.*, 2016, **4**, 99–122, DOI: [10.1002/ese3.117](https://doi.org/10.1002/ese3.117).
- 33 (a) P. Madejski, K. Chmiel, N. Subramanian and T. Kuś, *Energies*, 2022, **15**, 887, DOI: [10.3390/en15030887](https://doi.org/10.3390/en15030887); (b) A. I. Osman, M. Hefny, M. I. A. Abdel Maksoud, A. M. Elgahary and D. W. Rooney, *Environ. Chem. Lett.*, 2021, **19**, 797–849, DOI: [10.1007/s10311-020-01133-3](https://doi.org/10.1007/s10311-020-01133-3); (c) I. Ghiat and T. Al-Ansari, *J. CO₂ Utilization*, 2021, **45**, 101432, DOI: [10.1016/j.jcou.2020.101432](https://doi.org/10.1016/j.jcou.2020.101432).
- 34 J. de Brito and R. Kurda, *J. Cleaner Prod.*, 2021, **281**, 123558, DOI: [10.1016/j.jclepro.2020.123558](https://doi.org/10.1016/j.jclepro.2020.123558).
- 35 H. J. Ho, A. Iizuka and E. Shibata, *J. Cleaner Prod.*, 2021, **284**, 124785, DOI: [10.1016/j.jclepro.2020.124785](https://doi.org/10.1016/j.jclepro.2020.124785).
- 36 M. Peplow, *Nature*, 2022, **603**, 780–783, DOI: [10.1038/d41586-022-00807-y](https://doi.org/10.1038/d41586-022-00807-y).
- 37 J. Artz, T. E. MüllerOrcid, K. Thenert, J. Kleinekorte, R. Meys, A. Sternberg, A. Bardow and W. Leitner, *Chem. Rev.*, 2018, **118**, 434–504, DOI: [10.1021/acs.chemrev.7b00435](https://doi.org/10.1021/acs.chemrev.7b00435).
- 38 P. Lacy and J. Rutqvist, *Waste to Wealth, the Circular Economy Advantage*, Palgrave MacMillan, London, 2015, DOI: [10.1057/9781137530707](https://doi.org/10.1057/9781137530707).
- 39 (a) J. B. Zimmerman, P. T. Anastas, H. C. Erythropel and W. Leitner, *Science*, 2020, **367**(6476), 397–400, DOI: [10.1126/science.aay3060](https://doi.org/10.1126/science.aay3060); (b) Editorial, *Nature*, 2022, **604**, 598, DOI: [10.1038/d41586-022-01109-z](https://doi.org/10.1038/d41586-022-01109-z); (c) A. A. Jensen, L. Hoffman, B. T. Møller, A. Schmidt, K. Christiansen, J. Elkington and F. van Dijk, *Life cycle assessment: A guide to approaches, experiences and information sources*, European Environment Agency, Environmental Issues Series No. 6, 1997, Available at: <https://www.eea.europa.eu/publications/GH-07-97-595-EN-C/Issue-report-No-6.pdf>; (d) F. Piccinno, R. Hirschier, S. Seeger and C. Som, *J. Cleaner Prod.*, 2016, **135**, 1085–1097, DOI: [10.1016/j.jclepro.2016.06.164](https://doi.org/10.1016/j.jclepro.2016.06.164).
- 40 (a) C. Cathcart, *Chem. & Ind.*, 1990, **21**, 684–687, <https://www.scopus.com/record/display.uri?eid=2-s2.0-0025701217&origin=inward&txGid=7bf5ac423a6dba3205ae35566a11a257>; (b) P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, New York, 1998; (c) B. A. de Marco, B. S. Rechelo, E. G. Tótolí, A. C. Kogawa and H. R. N. Salgado, *Saudi Pharm. J.*, 2019, **27**, 1–8, DOI: [10.1016/j.jsps.2018.07.011](https://doi.org/10.1016/j.jsps.2018.07.011); (d) M. A. Murphy, *Substantia*, 2020, **4**, 15–57, DOI: [10.13128/Substantia-894](https://doi.org/10.13128/Substantia-894).
- 41 (a) H. C. Erythropel, J. B. Zimmerman, T. M. de Winter, L. Petitjean, F. Melnikov, C. H. Lam, A. W. Lounsbury, K. E. Mellor, N. Z. Janković, Q. Tu, L. N. Pincus, M. M. Falinski, W. Shi, P. Coish, D. L. Plata and P. T. Anastas, *Green Chem.*, 2018, **20**, 1929–2160, DOI: [10.1039/C8GC00482J](https://doi.org/10.1039/C8GC00482J); (b) R. Ratti, *SN Appl. Sci.*, 2020, **2**, 263, DOI: [10.1007/s42452-020-2019-6](https://doi.org/10.1007/s42452-020-2019-6).
- 42 (a) G. Centi and S. Perathoner, in *Sustainable Industrial Processes*, ed. F. Cavani, G. Centi, S. Perathoner and F. Trifiró, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2009, ch. 1, ISBN: 978-3-527-31552-9, https://www.wiley-vch.de/books/sample/3527315527_c01.pdf; (b) K. Kümmerer, *Angew. Chem., Int. Ed.*, 2017, **56**, 16420–16421, DOI: [10.1002/anie.201709949](https://doi.org/10.1002/anie.201709949); (c) D. J. C. Constable, *iScience*, 2021, **24**, 103489, DOI: [10.1016/j.isci.2021.103489](https://doi.org/10.1016/j.isci.2021.103489); (d) V. G. Zuin, I. Eilks, M. Elschami and K. Kümmerer, *Green Chem.*, 2021, **23**, 1594–1608, DOI: [10.1039/D0GC03313H](https://doi.org/10.1039/D0GC03313H).
- 43 (a) T. Keijer, V. Bakker and J. C. Sootweg, *Nat. Chem.*, 2019, **11**, 190–195, DOI: [10.1038/s41557-019-0226-9](https://doi.org/10.1038/s41557-019-0226-9); (b) K. Kümmerer, J. H. Clark and V. G. Zuin, *Science*, 2020, **367**, 369–370, DOI: [10.1126/science.aba49](https://doi.org/10.1126/science.aba49); (c) Z. Wang and S. Hellweg, *ACS Sustainable Chem. Eng.*, 2021, **9**, 6939–6951, DOI: [10.1021/acssuschemeng.1c00243](https://doi.org/10.1021/acssuschemeng.1c00243); (d) S. V. Mohan and R. Katkojwala, *Curr. Opin. Green Sustain. Chem.*, 2021, **28**, 100434, DOI: [10.1016/j.cogsc.2020.100434](https://doi.org/10.1016/j.cogsc.2020.100434).
- 44 Y. Geng, J. Sarkis and R. Bleischwitz, *Nature*, 2019, **565**, 153–155, DOI: [10.1038/d41586-019-00017-z](https://doi.org/10.1038/d41586-019-00017-z).
- 45 (a) P. G. Mahaffy and S. A. Matlin, *L'Actualité Chimique*, 2019, **446**, 47–49. Available at: <https://www.lactualitechimique.org/Pour-les-cent-ans-a-venir-reflexions-sur-l-enseignement-de-la-chimie-et-la-durabilite>; (b) H. Hopf, G. Mehta, A. Krief and S. A. Matlin, *Chem. Ind.*, 2017, **10**, 873–875. Available at: <https://www.chemistry.or.jp/opinion/ronsetsu1710-2e.pdf>; (c) S. Cornell, F. Berkhout, W. Tuinstra, J. D. Tàbara, J. Jäger,



- I. Chabay, B. de Wit, R. Langlais, D. Mills, P. Moll, I. M. Otto, A. Petersen, C. Pohl and L. van Kerkhoff, *Environ. Sci. Policy*, 2013, **28**, 60–70, DOI: [10.1016/j.envsci.2012.11.008](https://doi.org/10.1016/j.envsci.2012.11.008).
- 46 S. Kaza, L. C. Yao, P. Bhada-Tata and F. Van Woerden. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. World Bank, Washington DC, 2018, <https://openknowledge.worldbank.org/handle/10986/30317>.
- 47 S. A. Matlin, G. Mehta, H. Hopf, A. Krief, L. Keßler and K. Kümmerer, *Sustainable Chem. Pharm.*, 2020, **17**, 100312, DOI: [10.1016/j.scp.2020.100312](https://doi.org/10.1016/j.scp.2020.100312).
- 48 (a) V. Murthy and S. Ramakrishna, *Sustainability*, 2022, **14**, 647, DOI: [10.3390/su14020647](https://doi.org/10.3390/su14020647); (b) R. A. D. Arancon, C. S. K. Lin, K. M. Chan, T. H. Kwan and R. Luque, *Energy Sci. Eng.*, 2013, **1**, 53–71, DOI: [10.1002/ese3.9](https://doi.org/10.1002/ese3.9); (c) J. B. Rial and M. J. Ferreira, *Sci. Total Environ.*, 2022, **823**, 153370, <https://www.sciencedirect.com/science/article/pii/S0048969722004624>; (d) EU Directorate-General for Environment, *Waste prevention and management*, European Commission, 2022, https://ec.europa.eu/environment/green-growth/waste-prevention-and-management/index_en.htm; (e) D. T. Jerin, H. H. Sara, M. A. Radia, P. S. Hema, S. Hasana, S. A. Urme, C. Audia, M. T. Hasan and Z. Quayyum, *Heliyon*, 2022, **8**, e08918, DOI: [10.1016/j.heliyon.2022.e08918](https://doi.org/10.1016/j.heliyon.2022.e08918).
- 49 A. Wołos, D. Koszelewski, R. Roszak, S. Szymkuć, M. Moskal, R. Ostaszewski, B. T. Herrera, J. M. Maier, G. Brezicki, J. Samuel, J. A. M. Lummiss, D. T. McQuade, L. Rogers and B. A. Grzybowski, *Nature*, 2022, **604**, 668–676, DOI: [10.1038/s41586-022-04503-9](https://doi.org/10.1038/s41586-022-04503-9).
- 50 (a) T. F. G. Cova and A. C. Pais, *Front. Chem.*, 2019, **7**, 809, DOI: [10.3389/fchem.2019.00809](https://doi.org/10.3389/fchem.2019.00809); (b) S. Van Thienen, A. Clinton, M. Mahto and B. Sniderman, *Industry 4.0 and the chemicals industry*, Deloitte University Press, New York, 2016, Available at: <https://www2.deloitte.com/content/dam/Deloitte/de/Documents/consumer-industrial-products/Deloitte-Industry-4.0-and-the-chemicals-industry.pdf>.
- 51 J. L. Reymond, *Acc. Chem. Res.*, 2015, **48**, 722–730, DOI: [10.1021/ar500432k](https://doi.org/10.1021/ar500432k).
- 52 F. Strieth-Kalthoff, F. Sandfort, M. Kühnemund, F. R. Schäfer, H. Kuchen and F. Glorius, *Angew. Chem., Int. Ed.*, 2022, e202204647, DOI: [10.1002/anie.202204647](https://doi.org/10.1002/anie.202204647).
- 53 J. Elkington, *Harvard Business Review*, 2018, Available at: <https://hbr.org/2018/06/25-years-ago-i-coined-the-phrase-triple-bottom-line-heres-why-im-giving-up-on-it>.
- 54 (a) J. Tickner, K. Geiser and S. Baima, *Environ. Sci. Policy*, 2021, **63**, 4–15, DOI: [10.1080/00139157.2021.1979857](https://doi.org/10.1080/00139157.2021.1979857); (b) M. Brudermüller, *How to build a more climate-friendly chemical industry*, World Economic Forum Geneva, 2020, Available at: <https://www.weforum.org/agenda/2020/01/how-to-build-a-more-climate-friendly-chemical-industry/>; (c) A. W. Kolton, *The Chemical Industry: Part of the Climate Solution*, American Chemistry Council, Washington DC, 2020, Available at: <https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2020/the-chemical-industry-part-of-the-climate-solution>; (d) *The 2030 decarbonization challenge. The path to the future of energy*, Deloitte, New York, 2020, Available at: www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-eri-chemicals-decarbonization.pdf; (e) H. Olsen, *Tomorrow's climate-friendly chemical plants*, Technical University of Denmark, Kongens Lyngby, 2022, Available at: <https://www.dtu.dk/english/news/all-news/nyhed?id=35761fba-ed0f-4f64-bf63-002029b48066>.
- 55 R. Geres, A. Kohn, S. Lenz, F. Ausfelder, A. M. Bazzanella and A. Möller, *Roadmap Chemie 2050: Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland*, German Chemical Industry Association, Frankfurt, 2019, SBN: 978-3-89746-223-6, Available at: <https://www.vci.de/vci/downloads-vci/publikation/2019-10-09-studie-roadmap-chemie-2050-treibhausgasneutralitaet.pdf>.
- 56 (a) *The Montreal Protocol on Substances that Deplete the Ozone Layer*, United Nations Environment Programme, Nairobi, 2022, Available at: <https://ozone.unep.org/treaties/montreal-protocol>; (b) *Report of the World Summit on Sustainable Development*, United Nations, Johannesburg, New York, 2002, Doc. A/CONF.199/20, Available at: <https://daccess-ods.un.org/tmp/7030875.08678436.html>.
- 57 (a) A. Heaton, *Sources of Chemicals*, in *An Introduction to Industrial Chemistry*, ed. A. Heaton, Springer, Dordrecht, 1996, DOI: [10.1007/978-94-011-0613-9_3](https://doi.org/10.1007/978-94-011-0613-9_3); (b) H. Falcke, S. Holbrook, I. Clenahan, A. L. Carretero, T. Sanalan, T. Brinkmann, J. Roth, B. Zerger, S. Roudier and J. D. Sancho, *Best Available Techniques (BAT) Reference Document for the Production of Large Volume Organic Chemicals. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)*, European Commission, Brussels, 2017, Available at: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC109279_LVOC_Bref.pdf; (c) Ethene, *The Essential Chemical Industry – Online*, 4th January 2017, <https://www.essentialchemicalindustry.org/chemicals/ethene.html>.
- 58 E. Subbotina, T. Rukhijakan, M. D. Marquez-Medina, X. Yu, M. Johnsson and J. S. M. Samec, *Nat. Chem.*, 2021, **13**, 1118–1125, DOI: [10.1038/s41557-021-00783-2](https://doi.org/10.1038/s41557-021-00783-2).
- 59 (a) M. R. Finlay, *J. Ind. Ecol.*, 2003, **7**(3–4), 33–46, DOI: [10.1162/108819803323059389](https://doi.org/10.1162/108819803323059389); (b) F. Uekötter, *History and Technology*, 2021, **37**, 429–445, DOI: [10.1080/07341512.2022.2026135](https://doi.org/10.1080/07341512.2022.2026135); (c) *Quality Living Through Chemurgy and Green Chemistry*, ed. P. C. K. Lau, Springer-Verlag GmbH, Berlin, 2016, ISBN 978-3-662-53702-2.
- 60 (a) R. C. Thompson, C. J. Moore, F. S. vom Saal and S. H. Swan, *Philos. Trans. R. Soc., B*, 2009, **364**(1526), 2153–2166, DOI: [10.1098/rstb.2009.0053](https://doi.org/10.1098/rstb.2009.0053); (b) *Plastics and the Environment*, ed R. M. Harrison and R. E. Hester, Royal Society of Chemistry, London, 2018, <https://pubs.rsc.org/en/content/ebook/978-1-78801-241-6>; (c) R. Geyer, J. A. Jambeck and K. L. Law, *Sci. Adv.*, 2017, **3**, e170078, DOI: [10.1126/sciadv.1700782](https://doi.org/10.1126/sciadv.1700782).
- 61 (a) *Historic day in the campaign to beat plastic pollution: Nations commit to develop a legally binding agreement*, Press release, UN Environment Programme, Nairobi, 2 Mar 2022, <https://www.unep.org/news-and-stories/press-release/historic-day-campaign-beat-plastic-pollution-nations>



- commit-develop**; (b) R. Porta, *FEBS Open Bio*, 2021, **11**, 948–953, DOI: [10.1002/2211-5463.13122](https://doi.org/10.1002/2211-5463.13122).
- 62 A. R. Aves, L. E. Revell, S. Gaw, H. Ruffell, A. Schuddeboom, N. E. Wotherspoon, M. LaRue and A. J. McDonald, *Cryosphere*, 2022, **16**, 2127–2145, DOI: [10.5194/tc-16-2127-2022](https://doi.org/10.5194/tc-16-2127-2022).
- 63 (a) H. Lu, D. Diaz, N. J. Czarnecki, C. Zhu, W. Kim, R. Shroff, D. J. Acosta, B. R. Alexander, H. O. Cole, Y. Zhang, N. A. Lynd, A. D. Ellington and H. S. Alper, *Nature*, 2022, **604**, 662–667, DOI: [10.1038/s41586-022-04599-z](https://doi.org/10.1038/s41586-022-04599-z); (b) E. U. T. van Velzen and G. Santomas, *Nature*, 2022, **604**, 631–633, DOI: [10.1038/d41586-022-01075-6](https://doi.org/10.1038/d41586-022-01075-6); (c) J. Sun, A. Prabhu, S. T. N. Aroney and C. Rinke, *Microb. Genomics*, 2022, **8**, 000842, DOI: [10.1099/mgen.0.000842](https://doi.org/10.1099/mgen.0.000842).
- 64 (a) Editorial, *Nature*, 2021, **590**, 363–364, DOI: [10.1038/d41586-021-00391-7](https://doi.org/10.1038/d41586-021-00391-7); (b) C. Williams, *Chemistry World*, 5 May 2020, Available at: <https://www.chemistryworld.com/opinion/addressing-the-plastics-problem/4011557.article>; (c) R. A. Sheldon and M. Norton, *Green Chem.*, 2020, **22**, 6310–6322, DOI: [10.1039/D0GC02630A](https://doi.org/10.1039/D0GC02630A).
- 65 T. English, *Interesting Engineering*, 29 January 2021, Available at: <https://interestingengineering.com/real-life-use-every-element-periodic-table>.
- 66 (a) J. Morton, E. Tan, E. Leese and J. Cocker, *Toxicol. Lett.*, 2014, **231**, 179–193, DOI: [10.1016/j.toxlet.2014.08.019](https://doi.org/10.1016/j.toxlet.2014.08.019); (b) P. Chellan and P. J. Sadler, *Philos. Trans. R. Soc., A*, 2015, **373**, 20140182, DOI: [10.1098/rsta.2014.0182](https://doi.org/10.1098/rsta.2014.0182); (c) N. P. E. Barry and P. J. Sadler, *Chem. Commun.*, 2013, **49**, 5106–5131, DOI: [10.1039/C3CC41143E](https://doi.org/10.1039/C3CC41143E); (d) K. Sato, *Elements in Pharmaceutical Drugs*, TCIMail, 2013, vol. 158, pp. 2–5, <https://www.tcichemicals.com/assets/cms-pdfs/158Eall.pdf>.
- 67 (a) *Element Scarcity – EuChemS Periodic Table*, European Chemical Society, Brussels, 2021, Available at: <https://www.euchems.eu/euchems-periodic-table/>; (b) *Protecting Endangered Elements. Policy Workshop co-chaired by Ian Duncan and David Cole Hamilton*, Brussels, 22 September 2015, European Chemical Society, Brussels, 2015, Available at: <https://www.euchems.eu/communication/policy-workshops/protecting-endangered-elements/>.
- 68 (a) C. J. Rhodes, *Sci. Prog.*, 2019, **102**, 304–350, DOI: [10.1177/0036850419884873](https://doi.org/10.1177/0036850419884873); (b) S. A. Matlin, G. Mehta, H. Hopf and A. Krief, *Eur. J. Inorg. Chem.*, 2019, **39–40**, 4170–4173, DOI: [10.1002/ejic.201801409](https://doi.org/10.1002/ejic.201801409); (c) A. Cohen and J. C. Grant, *Foreign Policy Research Institute*, Philadelphia, 22 June 2021, <https://www.fpri.org/article/2021/06/americas-critical-strategic-vulnerability-rare-earth-elements/>; (d) *Critical raw materials*, European Commission, Brussels, 2022, https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en.
- 69 (a) J. D. Graham, J. A. Rupp and E. Brungard, *Sustainability*, 2021, **13**, 11274, DOI: [10.3390/su132011274](https://doi.org/10.3390/su132011274); (b) A. Amato, A. Becci, M. Villen-Guzman, C. Vereda-Alonso and F. Beolchini, *J. Cleaner Prod.*, 2021, **300**, 126954, DOI: [10.1016/j.jclepro.2021.126954](https://doi.org/10.1016/j.jclepro.2021.126954); (c) K. M. Abraham, *ACS Energy Lett.*, 2020, **5**, 3544–3547, DOI: [10.1021/acsenergylett.0c02181](https://doi.org/10.1021/acsenergylett.0c02181); (d) G. A. Collins, H. Geaney and K. M. Ryan, *J. Mater. Chem. A*, 2021, **9**, 14172–14213, DOI: [10.1039/D1TA00998B](https://doi.org/10.1039/D1TA00998B); (e) J. Biemolt, P. Jungbacker, T. van Teijlingen, N. Yan and G. Rothenberg, *Materials*, 2020, **13**, 425, DOI: [10.3390/ma13020425](https://doi.org/10.3390/ma13020425).
- 70 G. Mehta, S. E. Cornell, A. Krief, H. Hopf and S. A. Matlin, *Royal Society Open Science*, 2022, **9**, 212004, DOI: [10.1098/rsos.212004](https://doi.org/10.1098/rsos.212004).

