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Inventing a secure future: material stewardship as chemistry's mission for sustainability

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As the science of transformation of matter, chemistry provides knowledge, innovation and practice that are fundamental to the current efforts to achieve sustainability in the face of challenges that include multiple environmental crises (including pollution, climate change and biodiversity loss) and looming shortages of 'critical' materials. This article presents the case for chemistry and the chemical sciences adopting material stewardship as a central mission, whose aim is to transform and use the Earth's available stock of material resources in ways consistent with ensuring sustainability for people and for the physical and biological systems of the planet on which all life depends. The implications of this mission are examined, including for chemistry's contributions to extending knowledge, processes and products required for stewarding the Earth's physical and biological materials and systems. The mission includes supporting energy transitions necessary to stabilise Earth systems that are increasingly perturbed by anthropogenic effects. An overview is presented of how chemistry's mission of material stewardship interconnects with sustainability frameworks providing broad principles and goals, including the UN's Sustainable Development Goals and the Planetary Boundaries and Human Security frameworks, as well as with specific chemistry movements and orientations (including green, sustainable, circular and one-world chemistry) and enabling tools (*e.g.* systems thinking, material circularity and life cycle assessment) that provide guiding concepts, pathways and capacities for chemistry's contributions towards sustainability. The utility of the material stewardship mission is exemplified through three case studies, related to a product type, a sustainability tool, and a sustainability movement. The need is emphasised for the chemistry profession to work across disciplines to help shape policy and practice towards a sustainable future. This includes engaging with others in the processes of negotiation that shape global agreements on goals, policies and programmes that impact on sustainability. Critical ones currently in progress include the efforts to find mechanisms to reduce greenhouse gas emissions to limit global warming to the UN's target of not more than 1.5 °C above pre-industrial levels by 2050, and to establish a UN Science-Policy Panel on chemicals.

Sustainability spotlight

The extraction, transformation, use and disposal of the Earth's available stock of materials on a massive and increasing scale has substantial impact on the planet's physical and biological systems and is contributing to a range of environmental crises. We propose that chemistry, as the science of transformation of matter, now adopts a mission of material stewardship. This mission provides a comprehensive framing for the contributions of the chemical sciences to sustainability and brings together a diverse array of movements and tools in a coherent system of complementary efforts to limit or reverse the environmental impacts of anthropogenic materials. Chemistry's mission of material stewardship also encompasses a role in the stewardship of materials required for the transition to low-carbon energy. Adoption of the mission will contribute to meeting many of the UN sustainable development goals, including those for improving food nutrition and promoting sustainable agriculture (SDG 2), healthy lives (SDG 3), affordable, reliable, sustainable and modern energy (SDG 7), sustainable industrialization and fostering innovation (SDG 9), sustainable consumption and production (SDG 12), climate action (SDG 13) and conserving and sustainably using the oceans, seas and marine resources (SDG 14).

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1. Introduction

1.1 Chemistry and stewardship

Chemical substances and processes play a play a central role in the anthropogenic uses of natural resources for energy and for the conversion of matter on which modern life has come to depend. Multiple environmental crises emerging since the 19th Century have been driven by humankind's unsustainable[1] pace of exploitation of natural resources and flooding the planet with waste from both production and products, increasing the number of chemicals that are hazardous to human beings and the environment. The concept of stewardship of the Earth's physical and biological resources[2] is embedded in contemporary understanding of, and responses to, these environmental impacts of human activities. However, to date perspective on chemistry's key role in helping achieve sustainability have stopped short of embracing material stewardship as its core mission.

Here we set out in depth what 'material stewardship' means as an essential mission of chemistry and as a basis for defining and positioning 'chemistry for sustainability'. We provide

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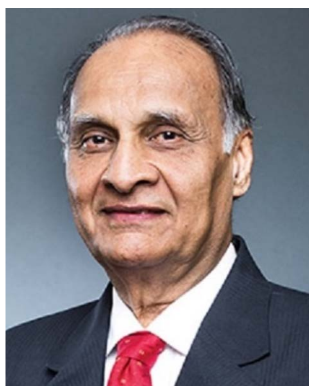

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a conceptual map depicting an integrated, relational view of the broad landscape of scientific, socio-economic and, policy factors that intertwine in understanding and pursuing this mission. Thus, we discuss how the mission of chemistry in material stewardship connects and integrates with a range of sustainability frameworks such as the United Nations Sustainable Development Goals (SDGs),[3] the Planetary Boundaries[4,5] and the Human Security Framework,[6] as well as with chemistry-centred movements and orientations (such as environmental,[7] green,[8] sustainable,[9] circular[10] and one-world[11] chemistry) that are already guiding the ongoing transition of chemistry towards its pivotal role in sustainability. As discussed in the case studies we present, material stewardship brings all of these together to provide a comprehensive and a coherent system directing the mission towards sustainability. Importantly, this aligns with the understanding that sustainability is an emergent property of the entire system and not simply a property of individual system components.[12]

Our intention is to introduce key themes that are of relevance to the mission of chemistry in material stewardship and with which chemists and those working in related chemical sciences and allied industries need to be familiar in undertaking – and appropriately reforming – education, research and practice, in order to contribute substantively towards a secure, sustainable future for people and for the physical and biological systems of the planet.

1.2 Sustainable development, sustainability and stewardship

The concept of stewardship has become inextricably entwined with two others – sustainable development and sustainability[13,14] – with diverse interpretations in different disciplines and sectors.[15] Sustainability and sustainable development are often conflated or considered as synonymous.[16] The contemporary understanding of sustainable development derives from the 1972 Club of Rome report, The Limits to Growth,[17] and the 1987 Brundtland Report,[18] which defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Further,[19] "Sustainability is the long-term maintenance and enhancement of human well-being within finite planetary resources… sustainability requires prioritising and making choices to assign resources to enhance human well-being within agreed environmental boundaries". This rendering captures a distinction[20] that sustainability is a long-term goal (*i.e.*, a more sustainable world), while sustainable development refers to the many processes and pathways to achieve it while recognising both the basic need for socio-economic development and limitations imposed by resource availability and by the environment's capability to cope with present and future requirements. Over time, the concept of sustainability has extended its concern from a local[21] to a planetary scale, expanding its ambit from individual resources to the entirety of Earth's coupled physical and biological systems. A systems perspective provides the important understanding that sustainability is a property that emerges from the integrated functioning of the whole system.[12,22] However, these articulations are focused on an anthropocentric goal of human well-being, while others have given stronger emphasis to protection and preservation of the biodiversity and resilient ecosystems of the planet as an essential objective of sustainability which is captured in SDG 15 (ref. 23) and the UN Convention on Biological Diversity.[24] In any event, given the clear need to manage material resources, chemistry's role in the quest for sustainability and sustainable development remains central.

A common thread running through many definitions and interpretations of sustainability and sustainable development is the identification of stewardship of the Earth's physical and biological resources as a necessary, shared responsibility of humanity. This concept of stewardship, entailing both a principle and processes for its application, can be found in records from ancient civilizations onwards and permeates many writings on cultural, economic, environmental, ethical, religious and social themes.[25] Ultimately resting on an ethical base that is future oriented,[15] stewardship encompasses planetary dimensions[26] and includes aspects relating to care and management of the biosphere, ecosystems, environment, landscape, and natural resources.[27–29] Thus, while caring for, managing, maintaining, and enhancing quality of life for people, the requirement for stewardship is extended to also cover the living beings that are affected by anthropogenic conditions but that do not have the capacity to regulate the underlying changes themselves.

1.3 Why chemistry has an essential role in material stewardship

The chemical sciences aim to understand and manipulate matter through chemical and physical transformations.[30] Given that many of the Earth system crises which threaten sustainability can be attributed, among other factors, to the enormous and accelerating scale[31] on which humanity is transforming matter, it is surprising that the role of chemistry in the overall stewardship of the Earth's material resources has received very little explicit scrutiny.[32] Within the broad concept of stewardship,[29] the specific domain of material stewardship provides a mission of strong relevance to orienting chemistry's core role in contributing to sustainability. Chemistry and related chemical sciences have an inherent responsibility to contribute to the stewardship of material (physical and biological) resources on which the ecological, economic and social systems of the planet depend.[33] But prior to 2019, the only recognised connections between chemistry and stewardship were in the context of supply security for critical minerals[34,35] and material sustainability for manufacturing,[36] product stewardship[37–39] and material efficiency in environmental stewardship.[40] Material stewardship, including in the chemical industry, has been referenced in relation to UN Sustainable Development Goal (SDG) 12 ("Ensure sustainable consumption and production patterns").[41,42]

We have previously signposted[43,44] the need for a comprehensive approach to chemistry's engagement in material stewardship. We proposed that chemistry should become a leading player in the stewardship of the stocks and flows of all the planet's material resources. This approach takes as chemistry's starting point the stewarding of the elemental heritage of the planet, acknowledging the finite amounts of the elements accessible for human use in the Earth's crust and atmosphere. Material stewardship intersects with planetary stewardship (described[45] as "the active shaping of trajectories of change on the planet, that integrates across scales from local to global, to enhance the combined sustainability of human well-being and the planet's ecosystems and non-living resources") and is essential in the face of Anthropocene challenges.[46] The shared stewardship responsibility for the Earth's biological as well as its physical resources carries the requirement that chemists also take account of the dependencies of many life-forms on the presence or absence of elements, compounds and complex materials in their environments. Movements like green, circular and sustainable chemistry all actively advocate for sustainability as a goal but differ in their scope.[47–49]

Material stewardship also has implications for chemistry in relation to sustainable energy. In addition to renewable sources such as wind and wave power, a massive supply of energy is available from the sun, but harnessing its full potential is limited by the available supply of materials necessary for capturing, storing and using this energy, as well as by the laws of thermodynamics. This indicates that chemistry (alongside other disciplines concerned with the transformation of matter, including physics and material science) has a key role[44] in stewarding the anthropogenic flow of energy as well as matter, as required for the energy transition necessary to greatly reduce, if not eliminate, greenhouse gas emissions (colloquially referred to as 'decarbonizing' energy).

2. Scoping key chemistry connections for material stewardship

2.1 A conceptual map linking chemistry, material stewardship and sustainability

Fig. 1 visualizes different levels through which chemistry can contribute to sustainability. In this conceptual map, chemistry, socio-economic and policy features are interwoven in the

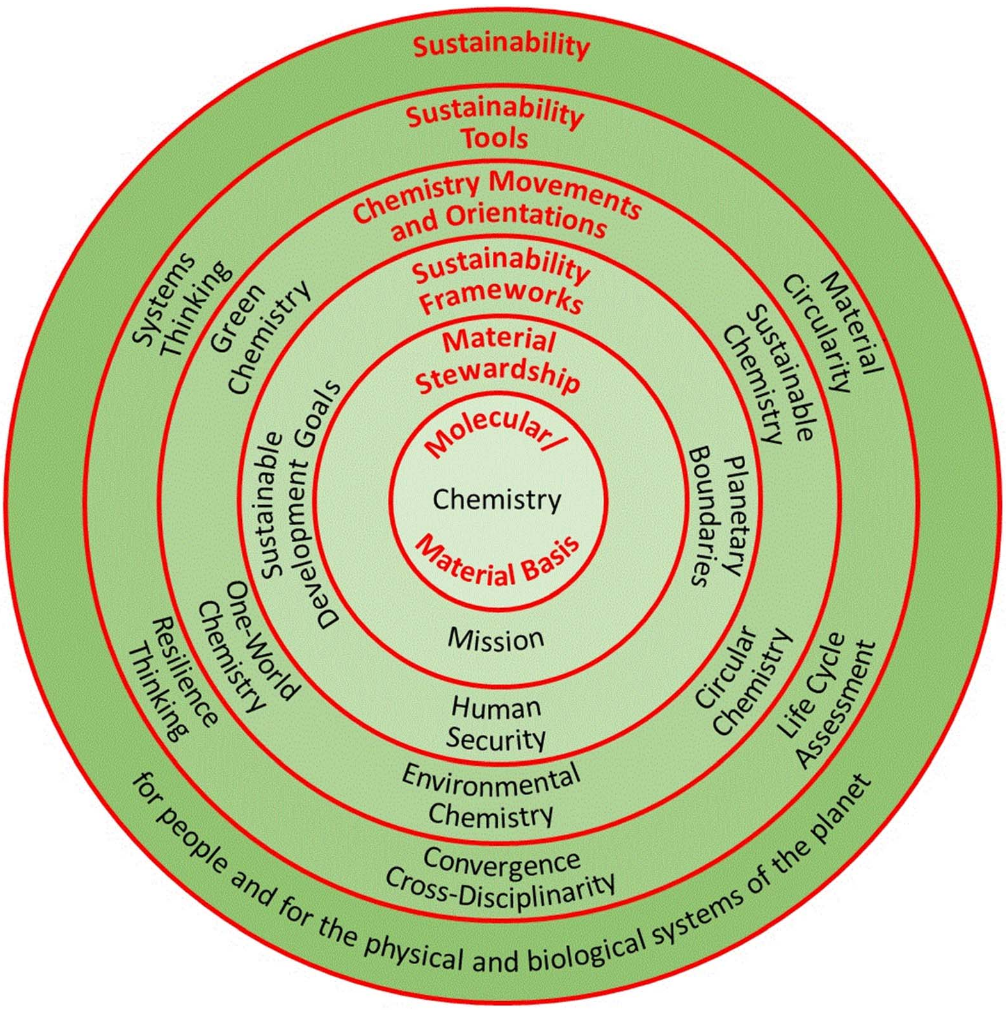

Fig. 1 Chemistry's contributions to sustainability, grounded in its molecular/material basis and mediated by a material stewardship mission, frameworks, chemistry movements and orientations, and tools.

evolving, complex, multi-sectoral efforts to achieve sustainability for people and for the physical and biological systems of the planet. Extending the previous mapping, in a pyramidal format, of concepts and relationships identified as significant for 'chemistry for sustainability',[22,44] this 'onion' model places chemistry centrally in the role of providing the material basis for sustainability. It presents material stewardship as the core mission for chemistry, through which sustainability can be achieved by a combination of frameworks, movements and tools. These are placed hierarchically, with those nearest the core providing guidance on the principles, motives and directions for application of those further away. Thus, pathways to achieving the mission of material stewardship are given direction and guidance by sustainability frameworks, with key ones being the seventeen SDGs, the nine Planetary Boundaries and the seven key dimensions of Human Security (see Section 1.1). For chemistry, the processes through which these frameworks are actioned are informed by movements and orientations that have been emerging over several decades and have dominated the directions and trajectories of advances in chemistry. These have included the complementary but distinctive approaches of environmental, green, sustainable, and circular chemistry, as well as one-world chemistry[11] which embraces the One Health principle[50] that the health of human beings, animals and ecosystems are intimately connected. They are enabled and facilitated by the application in chemistry of broad sustainability tools such as systems thinking, cross-disciplinary working, life-cycle assessment and material circularity, as well as by the developing understanding of the roles that chemistry plays[51] in building resilience. The 'chemistry for sustainability' model in Fig. 1 helps to flag both the contributions and limitations of any one framework, movement or tool on its own, pictorially representing the alignment of chemistry's mission in material stewardship with the understanding of sustainability as an emergent property of the entire Earth system.

2.2 Material stewardship as a chemistry mission

We propose that the mission of chemistry in material stewardship is to transform, use, and conserve the Earth's stock of chemical resources in ways consistent with ensuring sustainability for people and for the physical and biological systems of the planet on which all life depends (which may include deciding not to transform at all), through four critical domains of action:

• maintaining the availability of useable elemental resources to the highest possible extent,[52] which entails maximising their practically useful lifetimes, recognising the constraints of elemental stocks and ecological carrying capacities, while sourcing, producing, using and recycling materials in an environmentally and socially most responsible manner;

• advancing knowledge, processes and products necessary to the stewardship of the Earth's physical and biological materials and systems, through research and innovation, within chemistry itself (across education, research and industry) and through cross-disciplinary (convergent) collaborative work with other disciplines and sectors and with downstream users;

• enabling and supporting critical steps in meeting present and future challenges related to the sustainability of the planet's ecosystems and non-living resources, whose solutions depend on the interlinked stewarding of material and energy flows, such as the in the reduction of material flows and the current transitioning to renewable energy forms; and

• promoting greater understanding of the importance of material stewardship for sustainability, through reimagining education,[53] within the chemical sciences, in relation to other disciplines, and for society as a whole, to help shape policy and practice towards a more sustainable future.

2.3 Scope of material stewardship and chemistry's role

In the context of sustainability of Earth systems, stewardship broadly refers to a form of collaborative planning and responsible management of the environment through sustainable natural resource management practices that respect ecosystem functions.[29] Enqvist *et al.*[54] have noted that "current sustainability challenges – including biodiversity loss, pollution and land-use change – require new ways of understanding, acting in and caring for the landscapes we live in". They have analysed diverse meanings of stewardship and interconnected four key ones (ethic, motivation, action, outcome) using a framework based on three of its overlapping dimensions, identified as care (attachment/responsibility), knowledge (information/understanding) and agency (abilities/capacities) (Fig. 2). We have adapted this framework and terminology to the specific needs of a chemistry perspective, interpreting components of the three overlapping dimensions of stewardship, and using the framework as a guide to positioning and explaining chemistry's role in material stewardship, as discussed below.

2.3.1 Care: taking responsibility for stewarding the Earth's physical and biological resources. Several frameworks linked to

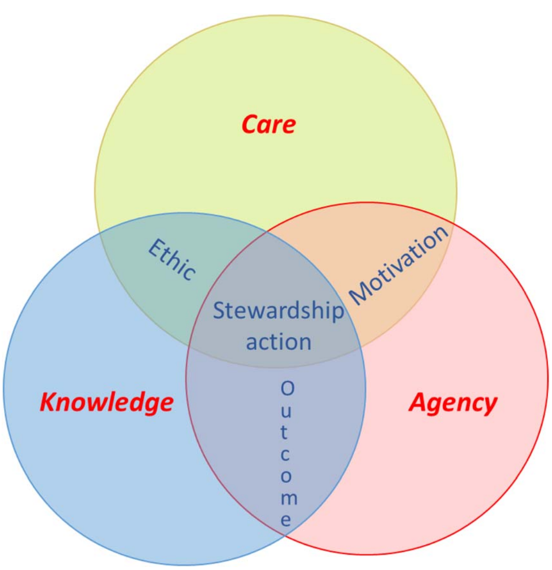

Fig. 2 Meanings and domains of stewardship guiding chemistry's role in material stewardship Reproduced from ref. 54 under CC BY-NC-ND license.

responsibility provide the ethic and motivation basis for stewardship that aims to ensure both human wellbeing and the sustainability of the planet's physical and biological resources and systems. Three of these frameworks, listed below, are of particular relevance to chemistry's role in sustainability, and for the first two cases chemistry's actual and further potential contributions have already been widely acknowledged and elaborated:

• Sustainable development goals: the SDGs are associated with the UN's Agenda 2030.[55] Since the approval for this Agenda by the UN General Assembly in 2015, there has been extensive discussion[9,56–59] of the contributions of chemistry in helping achieve sustainable development through the SDGs in general and specific ones such as those concerned with climate change, food, water and the environment.

• Planetary boundaries: this concept[5,60] provides a framework for examining critical Earth system processes (the linked dynamics of biosphere, atmosphere, cryosphere, hydrosphere and lithosphere) whose stability is being put at risk by the magnitude of perturbations caused by human activities. Nine Planetary Boundaries have been identified, with control variables and safe operating spaces quantified,[61] providing guidance for limiting environmental impacts at the global scale. The urgent need for proactive action[62] is signalled by the 2023 assessment, which reported that six of the nine boundaries are being transgressed, driving Earth system dynamics increasingly outside the safe operating space for humanity.[61] Chemistry has multiple roles in the Planetary Boundaries framework, including the identification and measurement of critical chemicals concerned in monitoring the Earth systems to which the boundaries relate, understanding the physical and biological distributions of the control variables and interactions leading to Earth system perturbations they cause, and development of practical solutions for their reduction and elimination.[63,64] Recently, a significant aspect of chemistry's response to the imperative to take its share of responsibility for stewardship at the planetary scale has started to be through its contributions to the development of benign-by-design[65–68] and safe-and-sustainable-by-design[69–74] products, processes and policies. However, these do not address the ever-increasing resource use.

• Human security: the human security framework developed by the UN[75,76] based on the 1994 Human Development Report[6] identifies seven main dimensions of human security (health, food, environmental, economic, personal, community and political security) which contribute to human and planetary wellbeing. In all these dimensions, science, technology and innovation have important roles to play, but only recently has the broad enabling contribution of chemistry been identified.[77] In framing chemistry's role in human security, it was underscored that repositioning itself as vital to human security affords chemistry a powerful opportunity to refresh itself as a science for the benefit of society, including as a sustainability science – but that in order to do so chemists will need to engage more directly and dynamically at the interface of science, society and policy.[77]

2.3.2 Knowledge: stewarding resources through applying information and understanding. Information and understanding help to illuminate the relationship between the ethic and outcome aspects of stewardship. In particular, understanding of intra- and inter-system effects connects the deliberation on why stewardship is necessary with assessment of tangible improvement of environmental conditions and progress toward general sustainability.

Chemistry has been a major contributor to the science base that has helped develop the understanding of Earth system behaviours and their vulnerabilities to anthropogenic activities. This has included recognition of the consequences of scale-up to global levels of activities that, at a local level, may seem of little significance for the wider environment but that cumulatively contribute to impairing entire ecosystem function. For example, chemistry informs about the impacts of biogeochemical natural and anthropogenic flows of carbon, nitrogen and phosphorus compounds, among many other substances, and of environmental pollution, such as by persistent organic pollutants[78] (see the case illustrated in Section 3.1) and plastic wastes, and chemistry reveals the molecular basis of the toxicology channels involved.

Applications of chemistry information and understanding are intrinsic to the approaches and terminologies that have been evolving in the efforts towards sustainability. An example is the case of hydrogen which, as well as being a key reagent in the Haber–Bosch synthesis of ammonia, is considered a leading contender to replace fossil fuels as a portable energy carrier and an important input to the synthesis of ammonia for use as a fuel, fertilizer, and domestic refrigerant.[22] Most hydrogen used industrially has been derived from the process of steam reforming of methane (eqn (1)) coupled with the water gas shift reaction (eqn (2)), which is a source of CO_2 emissions. Responding to the challenge of global warming, less environmentally damaging processes for sourcing hydrogen have been emerging and a spectrum of colours has been used in their nomenclature, on a range that reflects nuances both in chemical characteristics and environmental implications, from green (most environmentally benign, *e.g.* from water electrolysis using renewable energy) through colours including blue, grey, pink and brown to black (derived from fossil carbon and generating greenhouse gas).[79] It is not always clear that environmental implications are fully considered in these designations, for example, when poly- and per-fluoroalkyl substances (PFAS) are used for batteries or in membrane technologies to generate green hydrogen. Similarly, since carbon (in elemental and compound forms) is central both to biology and to a vast array of products useful to human beings, the “colour of carbon” also matters and is associated with nuanced definitions based on carbon function, attribute, or location.[80]

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \quad (1)$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad (2)$$

2.3.3 Agency: developing abilities and capacities to achieve stewardship goals. Relating motivation and outcome, the agency dimension of stewardship (Fig. 2) describes “the abilities and capacities of individuals, organizations and collaborative networks to engage in stewardship action and produce effects in the world", as well as capturing "the power of the biophysical landscape and material technology to affect the character of stewardship action".[29]

Chemistry's progression from being a utilitarian science[81] towards becoming an explicit sustainability science[82,83] has been marked by a number of movements and orientations. These have gathered pace since the mid-20th Century and have fortified abilities and capacities to contribute to aspects of material stewardship. They have included environmental,[84] green,[8,85,86] sustainable,[87–90] circular[10,91] and one-world[11] chemistry, signposting both the overall direction of change in approach and developing principles and tools to facilitate action. Resilience[92] (elasticity or adaptive capacity), already familiar to materials chemists in the context of the ability of a material to absorb energy when it is deformed elastically and release that energy upon unloading,[93] is among the most recent orientations to find its way into the lexicon of chemists concerned with sustainability. Chemistry's roles in resilience as an aspect of sustainability have been explored in the wider contexts of cross-disciplinary (convergent) working and the intersecting worlds of science, society and policy and the importance of engagement in advocacy has been highlighted.[51]

The ability/capacity aspect is also enabled by the availability of tools that facilitate action by setting out processes that channel analysis, reasoning and the mapping of productive pathways towards sustainability goals. Four such tools have emerged in recent years as being of general importance for sustainability (see the next-to-outermost circle in Fig. 1), and in each case is proving valuable in supporting the role of chemistry in the emergence of sustainability thinking and action:

• Systems thinking: holistic systems approaches contrast with reductionist approaches by adopting a set of synergistic analytic skills to improve capability to identify and understand systems, predict their behaviours, and devise modifications to produce desired effects predictably.[94,95] Systems thinking is broadly recognised as a transformative concept[96] and key competence[97,98] for sustainability. Since 2016, systems thinking approaches, as well as cross-disciplinary working, have begun to be adopted by chemistry, following the proposal that they are indispensable for chemistry's engagement in sustainable development as framed in the one-world chemistry concept.[11] Projects of the International Union of Pure and Applied Chemistry (IUPAC)[99,100] to incorporate systems thinking into chemistry have stimulated fresh approaches to education in chemistry.[101–103] These efforts have extended the availability of tools that enable the exploration of chemistry connections with Earth and societal systems, including the systems-oriented concept map extension (SOCME)[104,105] and planetary boundaries[106] visualisation graphics.

• Material circularity: reaction against the wasteful 'throw-away society' enabled by the availability of low-cost energy and cheap, mass-produced goods is leading to increasing attention to development of circular economy approaches.[107,108] Material circularity means extending the availability of valuable matter and lengthening the period before the accessible planetary stocks are exhausted, as well as reducing the amount of waste material requiring disposal, lessening the environmental burden (*i.e.*, aspects of material stewardship). However, material circularity on its own does not automatically produce sustainability, since not everything is recyclable and material circularity does not necessarily enquire into whether the material was sourced and produced sustainably in the first place, what new material and energy inputs are required for the specific recycling approach chosen, how side-products and wastes that are inevitably created at every stage along the recycling pathway are dealt with, or demand reduction in material and energy flows (see also Section 3.2 for further discussion of material circularity exemplified by an illustrative case).[109]

Stewardship of stocks and flows requires attention to both sources and fates of all raw materials, products and by-products[91] and to the energy required at all stages. On the input side, attention has mainly focused on security of supplies of those materials considered 'critical', 'strategic' or 'endangered'. Many of these, including rare earths and other metals, as well as non-metals such as phosphorus, silicon and germanium, are of strategic importance in areas such as the energy transition and microelectronics. In 2023, the European Commission (EC) listed 34 critical raw materials of importance because of their links to industry, modern technology and the environment.[110] Technologies in strategic economic sectors rely on these materials.[111] The 2019 report[1] of the International Resource Panel noted that material extraction had tripled over the last 50 years; the rate of extraction has accelerated since the year 2000; 90 per cent of biodiversity loss and water stress are caused by resource extraction and processing; and these activities contribute considerably to global greenhouse gas emissions. Among other measures, the report emphasised the need to improve resource efficiency and promote innovation for a circular economy. In the broader perspective of material stewardship, this requirement for recycling and recovery to maximise 'element circularity' can be extended, wherever practical, across the periodic table. On the other hand, when the entry of products or their metabolites into the environment cannot be prevented, it is important that they are designed for rapid mineralisation or degradation into benign materials.[112]

Waste (which is an economic concept, but refers to material which can also be an input to the economy) must also be included in the remit of material stewardship. Yu[113] has emphasised the value of interconnecting recycling loops in the circular economy to deal with different stages and different material components, creating a 'multi-loop resource nexus' where potential synergies arise from the interactions among different circular economies. She notes that such multi-loop approaches can be applied to organic and inorganic materials and are relevant to the recovery of valuable materials from food, agricultural wastes and municipal wastes. The need for more capacity is great: the World Bank's 2019 report on waste[114] noted that the world generates over 2 billion tonnes of municipal solid waste annually, expected to grow to 3.40 billion tonnes by 2050. Only a small fraction of municipal solid waste is subject to recovery and recycling, and the organic component, typically more than 50% of the total in any region, is a significant source of greenhouse gas emissions (estimated to be around 5% of global emissions in 2016) as well as other forms of pollution. The Food and Agriculture Organization has estimated[115] that a third or more of all the food produced in the world goes to waste, resulting not only in lost inputs such as water, fertilizer, pesticides and labour and the lost effect of nutrition but, when food waste decomposes in landfills, releasing CH_4 that is equivalent to 3.3 billion tonnes of CO_2 per year.

• Life cycle assessment (LCA): analysis of the whole life cycle of a material, from sourcing to end-of-use disposal, provides a further, complementary sustainability tool, affording quantitative assessment of the environmental impacts associated with a given product and enabling comparisons between alternative materials and processes.[116–119] Based in LCA, carrying capacities have been introduced[120] and 'absolute' environmental sustainability assessments (AESAs) have been developed to incorporate safe operating limits based on the planetary boundaries framework, enabling comparison of environmental impacts of products, companies, nations, *etc.*[121] AESAs of nearly 500 of the chemicals most extensively used in industry 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.[122] The need for impact-based metrics that can help chemists understand the connections between chemicals used and their potential for adverse effects on the physical and ecological environment environmental impact has been emphasised.[123,124] Jessop and MacDonald[125] have highlighted the value of the entire life cycle of a product in identifying hotspots that cause the most harm and using that information as the driver for the selection of new research projects and directions.

• Convergence or cross-disciplinarity: the capacity to work across boundaries of different disciplines and sectors and to understand and engage with intra- and inter-system processes is essential in addressing sustainability challenges. This has been increasingly recognised[126–128] and reflected in contemporary approaches to reforming chemistry education and steering it towards developing chemists with sustainability-related skills.[11,90,129–131]

2.4 Integrating chemistry, material stewardship and sustainability

In the care/knowledge/agency model (Fig. 2), the overlap between these three dimensions delineates the space within which stewardship action takes place. Enqvist *et al.*[54] have argued that stewardship may be considered a 'boundary object' – that is, a conceptual tool that enables collaboration and dialogue between different actors whilst allowing for differences in use and perception. Our analysis of material stewardship as the mission motivating chemistry for sustainability demonstrates that it does, indeed, supply this function.

3. Enabling engagements for chemists

Material stewardship provides a mission for chemistry that, in conjunction with key frameworks within the overall model of chemistry for sustainability set out in Fig. 1, helps systematise and bring additional value to chemistry's contributions to sustainability. Below are presented three illustrative cases, encompassing examples of a product type (fluorinated alkyl substances), a sustainability tool (material circularity), and a sustainability movement (Safe and Sustainable-by-Design – SSbD). In each case, the aim of the selected example is to provide an illustrative overview that points to the particular kinds of issues that become necessarily included in the sustainability picture when material stewardship provides the framing.

3.1 Poly- and per-fluorinated alkyl substances (PFAS)

More than 200 use categories and subcategories have been identified for commercial applications of PFAS,[132] with one particularly common area resulting from their water-repelling properties. Many applications are in commodities such as textiles (especially for outdoor wear), but also in ski waxes, technical applications such as hydrophobisation of metal surfaces and stain-resistant fabrics. Other categories of use include firefighting foams, the semiconductor industry (*e.g.*, in etching agents, anti-reflective coatings, photoresists, wafer thinning and as bonding ply in multilayer printed circuit boards); the energy sector (*e.g.*, in solar collectors and photovoltaic cells, and lithium-ion, vanadium redox, and zinc batteries, coatings for the blades of windmills) and carbon capture (*e.g.*, in the continuous separation of CO_2 in flue gases). They are used in some Li ion batteries and processes for hydrogen generation. Over seven million substances from the PFAS group, ranging in type from small molecules to polymers, can be found in chemical databases,[133] and several thousand of them are in use and appear to be environmentally relevant due their high persistence in the environment and bioaccumulative nature.[134] They have therefore experienced notoriety as 'eternal' or 'forever' chemicals'. Many of them are toxic to humans and the environment[135,136] and there are movements to ban or limit the use of PFAS in many parts of the world,[137,138] as well as efforts to remediate those PFAS now very widely distributed in the environment.[139,140]

Chemistry inputs to individual components of the family of sustainability frameworks, movements and tools (Fig. 1) might consider factors such as the service and function they should deliver, resulting end of life issues (time, and environmental compartment and/or economic sphere, circulating and recycling *vs.* ending up in the environment and what properties and fates are important there), comparing possible alternatives (chemicals as well as processes), resources needed to produce PFAS, as well as the waste and energy needs related to their synthesis, circulation and recycling, feasibility related to "costs" in the form of waste and energy, applying systems thinking comprehensively. Complementing conventional and green chemistry approaches, a chemistry systems thinking-based approach such as sustainable chemistry would first ask for the service and function needed and consider what alternatives there might be to obtain the service – or whether it is needed at all.[141] Thus, for example:

• In textiles, the service of faster drying, or remaining dry for longer, is often seen as desirable (even if not always needed in everyday-life textiles). This service is generally delivered by treatment of fibres with PFAS (which is not chemically bound and is therefore released into the environment during use and washing) but can also be obtained through plasma treatment followed by treatment with siloxanes. However, siloxanes also present environmental issues, such as being persistent in soil and water and forming persistent products of incomplete degradation in the atmosphere,[142] and might not be the best option, even if they are synthesised using green chemistry principles. Alternative processes using more benign chemicals are needed.[143] A stewardship approach incorporating sustainable chemistry and systems thinking would indicate that hydrophobised textile fibres should be used only in applications where this property is indispensable, *e.g.* special working clothes needed in extraordinary environments or activities, which would allow for easy separate collection and recycling, but not in everyday life. A number of clothing companies have banned PFAS in their products,[141] indicating that they are not needed (in contrast to earlier claims). If needed at all, textile hydrophobisation could be achieved by applying waxes which should be derived from renewable resources using green chemistry principles, with the possibility for later recycling being taken into account from the very beginning, and with environmental impact minimised.

• The service of hydrophobisation is sometimes needed for metal parts in certain applications, such as for energy efficiency or preventing corrosion. Rather than applying PFAS, which are not chemically bound to the metal's surface, a physical process such as abrasive laser treatment, can be used, again demonstrating a service- and function-based business model. This results in hydrophobisation by structuring the metal's surface on the nano scale level. In this case no chemical is needed, again avoiding all the related sustainability issues. In some cases, an alternative to laser abrasion might be the use of a polymer surface coating, but this requires consideration of the impact on recycling (*e.g.*, separation of metal and polymer, including additives if applied) and the need to source and synthesise the polymer following the principles of green chemistry.

• Firefighting fluids: extensive use of PFAS materials as foams for firefighting presents hazards both to those in close proximity to the substances (*e.g.*, exposure to PFAS foams has been associated with increased risks of cancer in firefighters) and to the general environment.[132,144] Fluorine-free firefighting foams are available and a report to the Stockholm Convention's Persistent Organic Pollutants Review Committee in 2018 emphasised the environmental benefits of switching to these alternatives.[145] However, a number of the substitutes entering use as alternatives to PFAS in recent years have not been properly evaluated and may also cause environmental damage.[146,147]

• Ski waxes are used to enable a higher speed and better ski adherence but end up directly in the environment. Not using PFAS would result in a small, if any, retardation effect and, if required by regulation, would be the same for all skiers. Clearly, ending use of PFAS in ski wax would not create an important service loss and all the related sustainability issues would be avoided. If competitive skiing wants to continue relying on technology support to some extent, rather than only the capabilities of the skier, chemists can undoubtedly design alternative waxes that would meet contemporary sustainability requirements.

PFAS provide an example of materials with 'persistence, mobility and toxicity' that are likely to be exceeding the proposed 'novel entities' planetary boundary.[64] For these substances, the material stewardship perspective highlights the overarching concern of environmental impact in addition to resource conservation, green synthesis or circularity. Movements towards restricting the use of PFAS and limiting their impact have relied on reducing molecular size and fluorine content (which, however, has done little to reduce their persistence) and on reducing uses to the 'essential' ones for which no present alternatives are known.[148] However, as emphasised in the Madrid Statement by more than 200 scientists,[149] a comprehensive approach is needed involving all the key stakeholders (scientists, governments, chemical manufacturers, product manufacturers, purchasing organizations, retailers, and individual consumers). The overall aim, in the stewardship of this material must be its phasing out from any large-scale use as quickly as possible, while applying the full range of material stewardship considerations to the development of appropriate alternatives where these are necessary and ensuring incentives for industry to innovate both material and non-material strategies.

This example illustrates an important feature of the material stewardship approach. It is not in competition with or contrary to the important sustainability frameworks, movements and tools incorporated in the model (Fig. 1). Rather, it combines them to provide a comprehensive and a coherent system, drawing on and applying their principles to specific cases as required to reach the best conclusion for sustainability. Furthermore, for a class of chemicals that have many applications and some 'critical' uses, but which have substantial risks for both human health and the environment, the example highlights the value of taking a material stewardship approach, guiding remediation efforts, regulation and the need to ensure the long-term impacts of substitution.

3.2 Material circularity

The circular economy aims first to reuse products themselves or second, by recycling, to recover valuable product constituents for further use (which could be in further manufacturing of the same product, or another one). The approach has potentials for economic benefit, for savings of material resources and energy and for generating less impact on the environment. For example, metallurgical processes may be required both for extraction from ores and recovery of metals from products, but in the latter case the mining stage is not needed, reducing environmental impact, and the resource of useable stock of the metal has its lifetime extended. Similarly, for plastics, their use for another purpose or, as second choice, remoulding or (if these two options are not practical) chemical depolymerisation reduces the need for extraction of staring materials from natural resources such as fossil oil or bio-resources.

However, material circularity on its own is not a guarantee of sustainability and every case must be examined in detail on its own merits. Not needing a material or product would be the best case in relation to respecting Earth system planetary boundaries. Furthermore, applying systems thinking would aid understanding which quality is needed for which application (a "fit for purpose" degree of quality of recycled and new materials, rather than prioritising the highest grade technologically possible or the materials bringing the greatest economic return). A material stewardship perspective highlights some key principles to apply in judging the merits of a claim:

• There is always waste (*i.e.*, increasing entropy) and material losses along the product lifecycle, including during manufacturing (*e.g.*, related to reaction yields, processing and separation inefficiencies), during use (*e.g.*, wear and tear, damage) incomplete collection, during recovery processing and in return to manufacturing. When used in combination with impact-based metrics, the E-factor (total mass of waste generated divided by the mass of the product manufactured) provides one simple measure to indicate where improvements can be made.[150]

• Contamination and blending of materials including intentionally added additives (*e.g.*, more than 10 000 are used in plastics alone)[151] in the initial cycle of manufacturing and use, as well as non-intentionally added substances (*e.g.*, contaminants acquired in plastics which are recycled),[152] may result in a progressive decrease in purity and downgrading of utility and value for each successive cycle. One consequence is that there is always need for extraction of new material from the primary source, to compensate for material loss, to allow for blending with recovered material to achieve the required product composition and to meet any increase in product demand.

• In addition to substances that will form part of the final product, and which tend to be the main focus of circularity considerations, full account must be taken of all the other materials consumed, all wastes produced and all the energy required for the entire operation of extraction, primary manufacturing, recovery and recycling. A product may have an extremely high recycling rate but be unsustainable because of one or more of these other factors. Life cycle thinking and assessment are key to understanding all the steps along the circularity pathway and generating data relevant for sustainability evaluation and can now be extended to link with impacts on Earth system planetary boundary through absolute environmental sustainability assessments (see Section 2.3.3). Since the operation of a circularity approach depends not only on technology factors but also on economics and societal factors (including regulatory, social and individual preference factors), it may be appropriate to also conduct social and socio-economic LCA.[153]

Sustainability must be understood as an emergent system property, rather than a property of any particular material or process alone (see Section 2.1). An example[154] which illustrates the comprehensive nature of the material stewardship perspective is the case of aluminium:

• The most abundant metallic element in the Earth's crust, aluminium is also one of the most highly recycled materials. About 200 billion aluminium cans per year are used globally, with about 75 percent on average being recycled in Europe,[155] and metal recovered from transport and structural applications is also extensively recycled. Of all of the aluminium produced in history (around 1.5 billion tonnes since commercial manufacture began in the 1880s), it is estimated that around 75 percent is still in use today, as proudly proclaimed by the aluminium industry.[156,157] However, answering the question of whether or not Al is 'sustainable' requires examination of both the economics and the chemistry involved.[154]

• The high rate of recycling of Al products is strongly driven by an economic factor. Production of primary Al metal is very expensive due to the extremely high power demand for the ore reduction process, while the recycling cost for recovered metal is much lower, because re-melting uses only 5% of the energy required for primary production. Used aluminium therefore retains high value for recycling.[158] However, most 'aluminium' in practical use consists of alloys (*e.g.*, 'aluminium' cans are usually made of alloys typically containing 92.5–97% Al, as well as Mg, Mn, Cr and trace amounts of Fe, Si and Cu). Up to 20% of other elements may be added to form Al alloys for different applications. Moreover, recovered material may also be contaminated (*e.g.*, with organic wastes, paints, plastic coatings). Consequently, Al scrap must be assessed, chemically analysed and graded and may require preliminary treatments before being remelted and blended with primary Al to create useful new materials (contrasting with the Al industry claim[159] that "aluminum can be recycled repeatedly, back into use, with no theoretical limitation"). Over 120 million tonnes of aluminium are currently produced per year, with about 35% coming from recycled metal, with annual demand for aluminium predicted to grow to more than three times this amount by 2050.

• Sustainability of material supplies and associated environmental footprint:

  ○ Tihe source of Al metal is bauxite, an ore containing Al_2O_3 mixed with compounds of Fe and other co-occurring elements including heavy metals and rare earths and with the presence of radioactive materials (Th, U). After mining, the crude ore is first processed by crushing and washing and then heated under pressure with a solution of sodium hydroxide (Bayer Process) to produce a solution from which aluminium hydroxide ($Al(OH)_3$) is precipitated, washed and heated to provide purified alumina. The substantial amount of energy required[160] is usually derived from fossil fuels.

  ○ The residue from digesting the crude bauxite is a highly alkaline side-product, mainly containing red iron oxide, as well as compounds of other co-occurring elements present in the source ore. Over 160 million tonnes of this toxic material, known as 'Red Mud', was produced alongside 126 Mt of purified alumina in 2018. Over more than a century, the environmentally safe disposal of the large amount of Red Mud generated while around 1 billion tonnes of aluminium has been produced has been a major, ongoing challenge which has still not been adequately solved globally.[161] More than 2.7 billion tons of Red Mud is estimated to be stored in tailings dams or ponds globally.[162] In 2010, a million cubic metres of Red Mud spilled into the River Danube from a reservoir at an alumina plant in western Hungary, creating a major ecological catastrophe.[163] Efforts have been made to find cost-efficient and environmentally sustainable techniques to dispose of Red Mud or to utilise it, including in cement, concrete and other composites and aggregates and as a catalyst.[164–167]

• Sustainability of energy supplies and associated environmental footprint:

○ The purified alumina is smelted by electrolysis of Al_2O_3 in a mix of molten cryolite and calcium fluoride at over 950 °C, reducing the oxide to Al metal which is run off in a molten state (>660 °C). Carbon electrodes are used in the electrochemical cell during the reaction and these are oxidised, releasing about 13 tonnes of CO_2 per tonne of Al produced. A range of other gaseous by-products (including CO_2, COS, SO_2, HF, CF_4 and C_2F_6) are also created under the reaction conditions and, along with the CO_2, are emitted to the atmosphere, with effects on global warming and atmospheric acidity. The electrochemical step is highly energy-intensive (about 15 kW h of electricity is required to produce 1 kg of Al) and this electric power alone accounts for about 20–40% of the overall cost of aluminium production, depending on the location of the smelter and source of electricity. Globally, about half of the electrolysis for aluminium production involves use of hydroelectricity, while carbon-based fuels account for 45%, adding another source of greenhouse gas to the footprint of aluminium production.

Thus, despite the high rate of recycling of aluminium, its current production overall is far from sustainable, since this is extremely energy-intensive, with significant amounts of energy along the route coming from carbon-based fuels, and the overall pathway (sourcing, extracting and manufacturing of the materials and products) generates a large amount of by-products with environmental impacts on land, water and atmosphere.[154] As the international aluminium industry itself acknowledges,[168] while the public currently hold the view that aluminium is a "green" and "environmentally friendly" material, the industry needs to take active steps in energy reduction if it is to avoid negative impacts on aluminium's "brand".

3.3 Safe and sustainable-by-design (SSbD) chemicals

The idea of designing safer chemicals was evident at least as far back as the early 1980s and variants of the concept are captured in the 12 principles of green chemistry and other US and European discourses of the 1990s.[169,170] It became the basis in the USA of the 'benign by design' movement and in Europe of the 'safe and sustainable-by-design' concept which was included, under the European Green Deal, in the European Chemicals Strategy and forms part of the EU's circular economy strategy.[171,172] SSbD represents a novel, although still voluntary, regulatory approach to enhancing safety and sustainability, serving as a form of "regulation by design".[173] The EU IRISS project, which incorporates SSbD, focuses early in the supply chain on providing products that are part of circular models while avoiding properties that may be harmful to human health or the environment. It integrates circularity, climate neutrality, functionality and safety of materials, products and processes throughout their life cycle.[174] In the EC communication on the chemicals strategy for sustainability, SSbD is defined as "a pre-market approach to chemicals that focuses on providing a function (or service), while avoiding volumes and chemical properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco) toxic, persistent, bio-accumulative or mobile. Overall sustainability should be ensured by minimising the environmental footprint of chemicals in particular on climate change, resource use, ecosystems and biodiversity from a lifecycle perspective". The SSbD framework proposes a hierarchical approach in which the safety aspects are considered first, followed by environmental and socio-economic aspects.[175] The development of a social sustainability dimension is proposed.[176] The SSbD aims to steer the innovation process towards the green and sustainable industrial transition; substitute or minimise the production and use of substances of concern, in line with, and beyond existing and upcoming regulatory obligations; and minimise the impact on health, climate and the environment during sourcing, production, use and end-of-life of chemicals, materials and products, including alternative business models.[175–178] By developing SSbD criteria for chemicals, providing support networks, addressing skills mismatches and competence gaps and ensuring that the legislation on industrial emissions promotes the use of safer chemicals by industry in the EU, the SSbD strategy aims to incentivize the European chemicals industry to prioritise innovation for substituting, as far as possible, substances of concern. These substances include primarily those related to circular economy, substances having a chronic effect for human health or the environment and those which hamper recycling for safe and high quality secondary raw materials.

Understanding what SSbD is in concept and in practice is still evolving.[179,180] At present, it appears to address some but not all aspects of the material stewardship mission. In particular:

• The 'sustainable' aspect is only partly covered, with SSbD's sustainability remit involving a combination of avoiding environmental harm and incorporating material circularity and waste prevention. Non-material alternative business models starting with service and function needs are not included. More explicit attention is required to sustainability related to service and function and in the initial sourcing of raw materials for production, including materials, energy and waste generation aspects.

• There is not yet a clear understanding about whether permissible safety and sustainability boundaries are, or should be, included. Boundaries are valuable to help all stakeholders aware of hazard and risk and to give significance to the results of tracking and identification of trends. However, a disadvantage is that once boundary limits are set, there is a temptation to approach them as closely as possible and a disincentive to aim towards lower levels. Moreover, boundaries can be difficult and controversial to set, as has proved the case with the novel entities planetary boundary, and the limits may change over time (in particular, moving to lower levels) as new information on environmental harms emerges. The material stewardship principles set out here (Section 2.2) point to the need for boundaries and safe operating spaces to the extent practical, as part of a hazard-based approach. They also point to application of a precautionary principle in areas where there is doubt, in alignment with the SSbD principle of avoiding harm to people and planet,[181] for example by generally reducing material and energy flows at all stages as well as diversity of chemicals in use. Full life cycle thinking, including end of life issues outside value-driven thinking, is needed.

3.4 Other examples

The three categories presented above (a product type, a sustainability tool, and a sustainability movement) to illustrate features of material stewardship as a mission for chemistry and to highlight benefits ensuing from its application were selected from a wide range of possibilities. For example, other categories where material stewardship can play a vital role include services (*e.g.*, communications, shelter, transport, energy conversion and storage, water-resistance), processes (*e.g.*, manufacturing, waste management and disposal) or human needs (*e.g.*, health, food and nutrition, water, security). Within each category, a multitude of specific examples provide options for exploring material stewardship concepts and implications for chemistry. To highlight just two of such cases:

• Lithium is of growing importance as a critical material in the energy transition now in progress, especially due to the increasing demand for lithium-based batteries for electric vehicles and other mobile power applications.[182,183] Material stewardship can be examined across the spectrum of sourcing, extraction, transformations, applications in energy conversion and storage, recovery and (all along the way) safety hazards, environmental risks and impacts.

• Phosphates have a wide range of important, large-scale uses, including in agriculture as primary source of nutrient phosphorus for plant and animal growth.[184,185] The material stewardship perspective across the spectrum of sourcing and extraction to disposal and recovery again highlights many concerns, including attention to the massive increase in the biogeochemical flow of P. This greatly exceeds the Planetary Boundary, with impacts on many aspects of the environment. Material stewardship challenges for chemistry include developing innovations that will conserve available stocks of P in useable forms, ensure supply is able to keep pace with burgeoning demand, and enable less wasteful and environmentally dispersive approaches to P uses in agriculture.

3.5 Concluding remarks

Adoption of material stewardship as a core mission for chemistry provides a comprehensive framework for educating about chemistry for sustainability, for considering the scope and urgency of areas for research and for industry to use both as guidance on areas of current practice requiring reform, and as a foresighting tool to anticipate the likely directions of future demands from regulators and society.

The mission for chemistry to be a sustainability science playing a central role in material stewardship necessitates that the chemistry profession, at individual and institutional levels across academia and industry, engages with chemistry learners to build knowledge, skills and competences beyond the traditional chemistry curriculum,[100] Many current initiatives in education are developing and applying fresh orientations to educating the next generation of chemists and other scientists regarding sustainability, including through focusing on a number of the key conceptual and practical building blocks represented in Fig. 1, such as green and sustainable chemistry[186–188] also including toxicology,[189] life cycle analysis,[190,191] systems thinking,[192,193] and cross-disciplinary/convergent approaches.[194–196] The combination of current approaches through their unification in the material stewardship mission offers a way to avoid fragmentation and competition between approaches.

The mission also interacts with society and policy-makers, bringing knowledge and an evidence-based approach to policy and actions for solutions to sustainability challenges. Societal engagement requires developing effective communication skills, channels and tools to help strengthen social trust and literacy in general, as well as to explain the case for material stewardship actions that society needs to support and advocating for action. Engagement with policy-makers requires a complementary set of communication skills in presenting policy-orientated evidence and making the case for particular actions, informed by understanding of economic, social and political factors that influence decision-making and outcomes.[28]

In the vitally important arena of engagement at international levels, it is necessary that chemical scientists and practitioners, including the downstream users of chemical products, become involved, in concert with others, in the processes of negotiation that shape global agreements on goals, policies and programmes that impact on sustainability. Critical initiatives currently in progress include the efforts to find mechanisms to achieve greenhouse gas reduction targets,[197] to deal, for example, with plastics pollution,[198] textile fast-fashion and e-waste generation and, for the UN Environment Programme, to establish a Science-Policy Panel (SPP) to contribute to the sound management of chemicals and waste to prevent pollution.[199] The process for creating the SPP has been initiated and provides an opportunity for chemistry societies and organizations, as well as governments, to input.[200–203] Steinhäuser *et al.*[204] have argued the case for a global binding framework for sustainable management of chemicals and materials which becomes a core pillar of international sustainability policy, with the SPP serving as its scientific advisory body. Chemists should use their available channels and circles of influence to participate in these processes to the fullest extent possible and bring a clear, coherent view of chemistry for sustainability to this global initiative which forms an important strand of effort towards material stewardship.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this perspective article.

Conflicts of interest

There are no conflicts of interest to declare.

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