IOCD

International Organization
for
Chemical Sciences in Development

Perspective

Sustainability and chemistry

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INTRODUCTION

The concept of sustainability has evolved alongside concerns about adverse impacts of human activity on the planet. Through interactions between civil society and national and inter-governmental agencies, during the last several decades a variety of agendas have emerged that attempt to focus attention and action on ways of reducing or eliminating these adverse impacts at local and global levels. While these agendas are all policy-oriented, they intrinsically – and usually explicitly – require fundamental inputs from science, technology and innovation (STI) at every stage – from recognizing and defining the problem, to establishing means of detection and monitoring key indicators and presenting viable solutions on a variety of time-scales.

The central importance of the chemical sciences to achieving the sustainability agendas has been reflected in a number of ways, including the emergence of Environmental Chemistry as a sub-discipline, the development of Green Chemistry principles and practices, the application of Life Cycle Analysis to the production, use and disposal of chemistry products and wastes, and the application of Circular Economy concepts to define emerging fields such as Circular Chemistry.

Despite these important signs of chemistry's increasing engagement with the challenges of sustainability, there have also been growing concerns about whether the ways in which chemistry has traditionally been taught and practiced are well-suited to addressing the complex issues involved. These concerns have been expressed in a number of calls for reform, with chemistry education being seen as fundamental to achieving a re-orientation in thinking about chemistry and its role, as well as a broadening of the concepts and skills imparted in chemistry courses to provide a stronger foundation of understanding of principles and issues and an increased capacity to contribute effectively to achieving sustainability goals.

This Perspective traces the evolution of sustainability concepts and agendas and draws out the linkages with chemistry. It discusses the emerging view that, to enhance chemistry's overall contribution to tackling sustainability challenges, chemistry needs to use systems thinking – to see the interconnections both among branches within the discipline itself and between chemistry and other disciplines and domains. Of particular importance are the overlaps between chemistry and Earth and societal systems.

SCIENCE, TECHNOLOGY, INNOVATION AND DEVELOPMENT

From the earliest period in human history, development of the capacity of our species to secure food, shelter and clothing, to move people and goods over long distances and to create materials enhancing the comfort and quality of living has been assisted by advances in technology that have provided new tools, processes and products. The emergence of the scientific method in the 16th-17th centuries in Europe gave a major boost to the innovation of new technologies, with growing impacts on agriculture and industry. From the 18th century onwards, the new science of chemistry, which had supplanted the old alchemical arts, began to make major contributions to innovations in diverse fields including agriculture, industry, medicine, energy, transport and overall economic growth.[1]

However, the practice of STI has not always had benign impacts. For example, non-renewable resources such as minerals have been extracted, transformed and used and materials emitted into the air, water and land in ways that have often caused environmental damage and pollution. Toxic effects have been seen in human beings and in many other species of living organisms. The extent of these impacts has grown with the rapidly burgeoning human population of the planet and increasing scale of agricultural and industrial activity. In effect, the Holocene Epoch – a geological period of 12,000 years of stability in the planetary environment since the last ice age – has now been supplanted by the Anthropocene. This epoch is characterized by the dominant role of overall human activity in shaping the planetary environment, including accelerated rates of carbon dioxide emissions and sea level rise, the global mass extinction of species, and the transformation of land by deforestation and development.[2]

Chemistry has contributed both to the benefits of advancing STI and to the adverse impacts that are now driving the Anthropocene (a term initially used by biologist Eugene Stoermer but first popularized by the atmospheric chemist and Nobel laureate Paul Crutzen in 2000).[3] It has become clear that chemistry must now focus on becoming a major contributor to solutions to these challenges – a science for the benefit of society providing the molecular basis of sustainability. The reorientation of chemistry education towards this objective is now a high priority.[4,5]

GLOBAL SUSTAINABILITY AGENDAS

Sustainability

Archaeological and historical analysis indicates that a focus on 'sustainability' is not an innate human behavioural capacity but must be specifically articulated and taught.[6] In Europe, the idea of sustainability seems to have first emerged in forestry, at least as early as in the 13th century. Later, a clear articulation of the 'sustainability' concept, named 'Nachhaltigkeit' in German, was seen in the work of Hans Carl Von Carlowitz (1645–1714), who identified that Saxony's silver mining and metallurgy industries placed a very high demand on timber supplies, with devastating consequences for local forests. He formulated ideas for the "sustainable use" of the forest, with scheduled reforestation by sowing and planting. A 1795 paper by Georg Ludwig Hartig called not only for woods to be used as efficiently as possible, but also for consideration of the needs of future generations – a stipulation later to become the cornerstone of 'sustainable development'.[7,8,9] Sustainability continued to be discussed in the domain of forestry and the translated term derived from the German appeared in English in the mid-19th century. The US forester and politician Gifford Pinchot (1865-1946) promoted scientific forestry and was the first to demonstrate the practicality and profitability of managing forests for continuous cropping.[10]

A separate strand of thinking about sustainability was marked by the writings of Thomas Robert Malthus (1766 – 1834). In his 1798 *Essay on the Principle of Population as It Affects the Future Improvement of Society,* Malthus expressed concern that the rate of population growth was far outstripping the rate of increase in agricultural production at the time.[11] The 18th-19th century mechanized agriculture revolution meant that Malthus' fears of mass starvation proved groundless in the short term. The development of agrochemicals and the innovations of the Green Revolution in the 20th century again averted a global food crisis while the Earth's population was growing from 1.6 billion in 1900 to 6.1 billion in 2000. However, in the 21st century, food security concerns have again resurfaced as the world faces the challenges of how to increase food production by around 70% from the 2010 level to feed a population that will reach 9-10 billion by 2050 – and what the impacts of this will be on the planetary environment.[12]

Sustainable Development

Concern that the food, energy and material demands and the waste outputs of the total population of the Earth are, or soon will be, exceeding the carrying capacity of the planet is now a central factor in discourses on sustainability.[13] Historically, 'sustainable development' has emerged from as a synthesis of diverse components (including ecological, economic, financial, social, political and institutional) in efforts to try to increase the compatibility of ecological, economic and social sustainability[14] and to give each equal importance in decision making[15] in what has become known as the 'triple bottom line' approach.[16] This sees sustainable development as a pathway to the ultimate goal of sustainability in the sense of reaching human-ecosystem equilibrium.[17]

Some important milestones on the route to the current conceptualization of sustainable development were seen in the 1960s. Rachel Carson's 1962 book *Silent Spring*[18] warned of the ecological damage being caused by the widespread use of some pesticides and herbicides in agriculture. In an influential 1966 essay, *The Economics of the Coming Spaceship Earth,* Kenneth Boulding identified the need for the economic system to fit itself to the ecological system with its limited pools of resources.[19] The Club of Rome[20] was founded in 1968 and its 1972 book *The Limits to Growth* provided a stark warning about the growing impact of unbridled consumption and offered as an alternative the concept of a sustainable world which would avoid "overshoot and collapse" of the global system as the consequence of interactions between the Earth's and human systems.[21]

The UN's first major conference on international environmental issues was held in Stockholm[22] in 1972 and reflected the growing environmental concerns of the previous decade. Its non-binding Declaration referred to a human being's "fundamental right to ... adequate conditions of life, in an environment of a quality that permits a life of dignity and well-being" and to the responsibility of each State not to cause damage to the environment of other States or to areas beyond national jurisdiction or control.[23] As an outcome of the Stockholm conference, the UN Environment Programme (UNEP)[24] was established in Nairobi in 1972 and has played a significant role in developing international environmental conventions and promoting environmental science and information.

In 1983, the UN established a World Commission on Environment and Development (WCED) chaired by Gro Harlem Brundtland. It's Report, *Our Common Future*,[25] published in 1987, developed the broad political concept of sustainable development, defining it as ***"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*** The Brundtland Report recognized that the many crises facing the planet are interlocking and constitute elements of a single crisis of the whole and there is a vital need for the active participation of all sectors of society in consultation and decisions relating to sustainable development. The WCED Report paved the way for the UN Conference on Environment and Development ('Earth Summit')[26] held in Rio de Janeiro in 1992 and follow-on conferences in Johannesburg[27] in 2002 and Rio de Janeiro (Rio+20)[28] in 2012.

Historically, the spread of sustainability concerns out of the domain of science and into the world of politics and intergovernmental negotiations and treaties has been essential as a basis for ensuring global-scale action on global challenges. But it has also been the source of complications, since politicians inevitably appropriate causes in ways that reflect their own political principles, movements and ambitions. For example, politicians and developers will sometimes use the term 'sustainable growth' as a synonym for 'sustainable development'. Ulhoi and Madsen pointed out that this is either a misunderstanding based on a superficial knowledge about the meaning of the sustainability concept, or it is being cynically used to make the traditional growth philosophy more acceptable in an age of increasing environmental concern. Writing in 1999, they considered that, in most cases, environmental responses from industry had thus far shown little resemblance with a basic systems approach to the concept of sustainability, while such an approach could facilitate development that is ecologically and economically more sustainable.[29]

The example of atmospheric ozone destruction by chlorofluorocarbons (CFCs) illustrates these complexities and demonstrates the central role of chemistry and systems thinking in identifying and solving critical problems in sustainable development. Improved synthetic routes to CFCs were developed in the late 1920s and, as the first refrigerant that was non-toxic and non-flammable, dichlorodifluoromethane (Freon) was widely used in domestic refrigerators from 1930, while other CFCs soon found applications as fire extinguishing agents, foaming materials and aerosol propellants.[30] However, following James Lovelock's invention of the electron capture detector in 1957, in the late 1960s he demonstrated that traces of CFCs could be detected in the atmosphere.[31,32] These chemically inert gases accumulate in the stratosphere and in 1974 Mario Molina and Sherwood Rowland (who shared the 1995 Nobel Prize with Paul Crutzen) published their findings that the photolysis of atmospheric CFCs by sunlight releases chlorine atoms and these break down ozone.[33]

There was immediate alarm, which focused both on the environmental damage itself and on the attendant increased risks of skin cancer. Public boycotts of CFC-driven aerosols for domestic use rapidly undermined the market for these products. The interaction of chemistry, biology and environmental systems had reached a crisis point and public opinion demanded immediate, global action. In 1977 UNEP adopted a World Plan of Action on the Ozone Layer, which called for intensive international research and monitoring of the ozone layer; and in 1981 UNEP began work on drafting a global framework convention on stratospheric ozone protection, to which there was initially strong opposition from industry and some governments. In the Vienna Convention, concluded in 1985, States agreed to cooperate in research and scientific assessments of the ozone problem. However, specific limits on chemicals that deplete the ozone layer were only set two years later when, following a change in position by industry, the Montreal Protocol on Substances that Deplete the Ozone Layer[34] was signed. The Protocol required rapid phasing out of CFCs and slower phasing out by 2030 of hydrochlorofluorocarbons (HCFCs), which are less damaging to the ozone layer but are nevertheless powerful greenhouse gases.[35] Richard Benedick, who headed the US delegation in many of the ozone negotiations, commented[36] that ***there was a need "to bridge traditional scientific disciplines and examine the earth as an interrelated system of physical, chemical, and biological processes"*** – a good example where systems thinking was central to understanding and responding to a global challenge.

Planetary Boundaries

The concept of planetary boundaries was presented by *Rockström, Steffen and colleagues in 2009, when they proposed* nine Earth system processes of critical importance for sustainable development. ***Boundaries were identified that define a "safe operating space for humanity"*** and updated quantitative estimates for several of the boundaries were published in 2015.[37,38] The nine planetary boundaries form three groups:

- Boundaries defining a safe global level of depleting non-renewable fossil resources, such as energy (coal, oil, gas), and fossil groundwater;
- Boundaries defining a safe global level of using the living biosphere, including exploitation of ecosystems, protection of biodiversity and consuming renewable resources, such as land use;
- Boundaries providing a safe global level of Earth's capacity to absorb and dissipate human waste flows, including carbon, nitrogen, phosphorus, and toxic chemicals such as pesticides.

Three of the boundaries concern biogeochemical flows of elements that are relatively abundant in either the Earth's crust (carbon: 0.18%; phosphorus: 0.1%) or atmosphere (nitrogen: 0.002% in the crust and 78% of the atmosphere). The central problem in each case concerns the extent to which very large-scale uses are contributing to major environmental changes – for example, generation of greenhouse gases from combustion of carbon-rich materials to produce energy, pollution of the atmosphere and water by nitrogen oxides and nitrates from the production of nitrate fertilizers, and pollution of water from the use of phosphate fertilizers (the massive use of which is predicted[39,40] will result in shortages of phosphates in the next 50-100 years).

The planetary boundaries concept fed into the formulation of the UN Sustainable Development Goals (SDGs).[41]

UN Sustainable Development Goals

A series of world conferences during the last three decades of the 20th century addressed diverse aspects of international development (e.g. relating to children, education, health, human rights, population and women) and aimed to close the large – and in many cases growing – gaps between richer and poorer countries. These coalesced in 2000 in the UN Millennium Summit, which agreed a set of eight Millennium Development Goals (MDGs) and associated detailed targets for 2015, through which richer countries aimed to assist poorer ones to catch up.

A Task Force appointed by the UN Secretary General for the UN Millennium Project[42] underscored the critical importance of STI for development in every country, to provide the capacity respond to challenges in areas such as economic productivity, agriculture, education, gender inequity, health, water, sanitation, environment, and participation in the global economy. Key areas for policy action were identified, including focusing on platform (generic) technologies, improving infrastructure services as a foundation for technology, improving higher education in science and engineering and redefining the role of universities, promoting business activities in STI, improving the policy environment and focusing on areas of underfunded research for development. Among the platform areas highlighted were chemistry and several other molecular science disciplines such as biotechnology, nanotechnology, and new materials and the Report called for increased investment in science and technology education and re-orientation in curricula and pedagogy towards contributing to development.

The MDGs became the central driving force of international development work in the period to 2015. Improvements were seen in many areas, including poverty levels, maternal and child health, primary education participation rates, including for girls, access to clean water and sanitation. But many targets were missed and the MDGs were frequently criticized – including for lack of ownership that poorer countries had felt for the process through which they had been formulated, for a one-sided approach to development based on a donor-recipient framing and for lack of comprehensiveness since they only dealt with specific issues (e.g. primary education, rather than multi-level education; specific infectious diseases rather than health as a whole).

Meanwhile, growing concern about the environment had also emerged on the global political stage. At the same time that the ozone-damaging effects of CFCs in the atmosphere were causing widespread alarm, a 1975 paper by US geophysicist Wallace Smith Broecker[43] predicted that rising carbon dioxide levels in the atmosphere would lead to pronounced temperature rises and brought the term ‘global warming’ into common use. The interconnections between ozone-depleting and ‘greenhouse’ gases like CO_2, CH_4, N_2O and HCFCs became apparent and, as well as being recognised in the Montreal Protocol, soon lead to separate global intergovernmental discussions and negotiations. The UN Framework Convention on Climate Change (UNFCCC), which opened for signature at the Rio Earth Summit in June 1992, aimed to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. It was eventually ratified by all UN Member States, but did not set binding limits on greenhouse gas emissions for individual countries, or contain enforcement mechanisms.

The Kyoto Protocol to the UNFCCC, which was adopted in Kyoto, Japan, in 1997 and entered into force in 2005, set internationally binding emission reduction targets for greenhouse gasses.[44] However, a number of leading emitters of greenhouse gases, including the USA, China and India, never ratified the Protocol and Canada withdrew in 2012. Negotiations for the successor to the Kyoto Protocol culminated in the Paris Agreement on Climate Change, which aimed to strengthen the global response to the threat of climate change by keeping a global temperature rise in the 21st century well below 2ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 ºC. Additionally, the agreement aimed to strengthen the ability of countries to deal with the impacts of climate change.[45] Up to May 2020, 189 (188 states plus the European Union) of the 197 Parties to the UNFCCC had ratified the Paris Agreement, including China, the United States and India, which are among the largest greenhouse gas emitters within the UNFCCC membership and collectively responsible for about 42% of these emissions globally. However, in 2017 the USA announced its intention to leave the Paris Agreement at the earliest possible time,[46] in November 2020.

Political momentum increased for a more comprehensive and balanced follow-on to the MDGs that would incorporate concerns about the environment and sustainable development. The 2012 Rio+20 conference established a joint UN consultation and negotiation process, involving both government and civil society representatives, which led to the formulation of the UN 2030 Agenda for Sustainable Development and the 17 goals and 169 targets of the UN Sustainable Development Goals (SDGs), adopted by all Member States in 2015 (Figure 1).[47,48]

Figure 1 UN Sustainable Development Goals agreed in 2015

Goal 1: End poverty in all its forms everywhere
Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture
Goal 3: Ensure healthy lives and promote well-being for all at all ages
Goal 4: Ensure inclusive and quality education for all and promote lifelong learning
Goal 5: Achieve gender equality and empower all women and girls
Goal 6: Ensure access to water and sanitation for all
Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8: Promote inclusive and sustainable economic growth, employment and decent work for all
Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation
Goal 10: Reduce inequality within and among countries
Goal 11: Make cities inclusive, safe, resilient and sustainable
Goal 12: Ensure sustainable consumption and production patterns
Goal 13: Take urgent action to combat climate change and its impacts
Goal 14: Conserve and sustainably use the oceans, seas and marine resources
Goal 15: Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss
Goal 16: Promote just, peaceful and inclusive societies
Goal 17: Revitalize the global partnership for sustainable development

The SDGs broke new ground in a number of ways. Development was recast as a universal enterprise with responsibility and ownership shared among all nations; there was an in-built equity demand to "leave no-one behind"; environmental concerns were incorporated in the international development agenda to a greater extent than before; all countries, including poor ones, were recognized as stewards of planetary resources for all humanity; and the importance of follow-up and review was emphasized, with a focus on specific indicators.

CHEMISTRY AND THE CHALLENGES OF SUSTAINABILITY

Chemistry has been intimately connected with all stages of the unfolding challenge of sustainability. It is important to acknowledge that it has contributed to creating the problem, through the impacts of chemical processes and products on the global environment. But chemistry is also essential to the solutions – helping to identify, detect and monitor indicators; find ways of reducing consumption, waste and pollution; clean the environment and mitigate adverse impacts.

A number of developments in chemistry's orientation reflect the evolution of thinking about chemistry's role in contributing to sustainable development:

Environmental Chemistry

Environmental chemistry is a multidisciplinary science that studies the sources, reactions, transport, effects, and fate of chemical species in the air, water, and land, and the effect of human activities upon the various environmental segments, such as atmosphere, hydrosphere, lithosphere, and biosphere. Studies of the chemistry that occurs in different natural environments and the impacts of chemicals introduced into these environments began in the 19th century – for example, with the work of John Tyndall in the UK and Svante Arrhenius in Sweden on the effects of carbon dioxide in the atmosphere on temperature.[49] Courses teaching Environmental Chemistry became popular in Europe and the USA from the 1960s and demand for graduates in this field were boosted by the growth in legislation and in regulatory agency action on pollution.

By the 1990s, there was an increasing shift in focus from policy approaches that emphasized pollution control to ones that aimed at pollution prevention, moving the scientific focus upstream to consider from the outset how materials would be sourced and handled and how by-products, waste products and end-of use products would be safely managed and disposed of or recycled. This reframing required new ways for chemistry to engage and paved the way for the birth of 'green chemistry'.[50]

Green Chemistry

This movement emerged from a variety of ideas and concerns including atom economy,[51] chemical pollution, resource depletion, movement from reduction of industrial emissions at the 'end of the pipe' toward the active prevention of pollution through the innovative design of production technologies themselves ('benign by design'), 'clean' and 'sustainable' chemistry. These coalesced in the 1998 publication on green chemistry principles and practice by Paul Anastas and John Warner.[52] The principles have subsequently been extensively adopted[53] and introduced into chemistry education.[54]

Life-Cycle Assessment

From the 1960s onwards, there were growing requirements in some countries for environmental impact assessments to be made before the introduction of new processes and products. An important contribution to the process of conducting such assessments is made by life cycle assessment,[55] an analysis which considers all steps from the acquisition of raw materials to the disposal or recycling of waste- and end-products. Each source, process and material is examined from several perspectives, for example bringing in Green Chemistry approaches and knowledge of toxicology, environmental dispersal and degradation routes and ecology of the relevant surroundings. This creates an overall picture of the likely environmental impacts and allows alternatives to be compared.

One-World Chemistry

In 2015, the International Organization for Chemical Sciences in Development (IOCD) responded to the newly adopted UN 2030 Agenda, highlighting the central contribution that chemistry can make in achieving the SDGs.[56] Chemistry's well-established capacities for innovation and as the basis of a wide range of technologies can be drivers in poverty reduction and inclusive, sustainable economic growth and industrialization (Goals 1,8,9) that help reduce inequalities and make urban environments resilient and sustainable (Goals 10,11) and that help avert and mitigate climate change and its impacts and provide pathways to address environmental damage to air, sea and land (Goals 13,14,15). Chemistry can help furnish new agricultural and pharmaceutical processes and products (Goal 2,3) as well as more efficient and more sustainable processes for providing clean water, sanitation, energy and sustainable production (Goals 6,7,12). It can play a role in the delivery of quality education and lifelong learning that is based in gender equality and empowerment (Goal 4), assist in countering military uses of chemical warfare and promoting disarmament and the peaceful uses of technology (Goal 16) and, across all these areas, chemistry can operate through global partnerships and alliances that work for collective benefit to the health, well-being and sustainable development of all people (Goal 17).

IOCD also emphasized that, to make its optimum contribution, chemistry would need to undergo fundamental changes in its orientation and approaches, including in education.[56] This view was echoed by others in academia and industry, for example in relation to Green Chemistry.[57,58]

IOCD went on to delineate the changes in chemistry education and practice that would be needed, advancing the concept of 'one-world chemistry'.[59] This concept re-positions chemistry as a science for the benefit of society - a 'sustainability science' rooted in ethical principles and practices, adopting sustainability principles, embracing systems thinking and working across disciplines to tackle contemporary global challenges.[60] Systems thinking has been identified as one of five key competencies that are essential for sustainability.[61]

3R Initiative, the Circular Economy and Circular Chemistry

The 3R Initiative, (Reduce, Reuse and Recycle),[62] which seeks to make effective use of cycling of resources and materials, was agreed by the 2004 G8 Summit. It has subsequently been adopted by many countries and has become a core feature of the 'circular economy' concept.[63] This approach aims at breaking the global 'take, make, consume and dispose' pattern of growth – a linear model implying that resources are abundant, available, easy to source and cheap to dispose of – and makes use of life-cycle analysis.

The circular economy concept has been applied specifically to 'circular chemistry', for example, in providing design considerations for research and process development in the chemical sciences that emphasizes "the role of chemists in a world without waste", [64] in the development of a circular carbon economy aiming to achieve net zero emissions, resource efficiency and conservation through a coupling of the energy, chemical and waste management sectors, [65] The circular economy concept has been used to draw a set of twelve principles, (Table 1) analogous to but extending beyond those originally enunciated for green chemistry, [66]

Table 1 The twelve principles of circular chemistry

1. Collect and use waste. Waste is a valuable resource that should be transformed into marketable products.	7. Target optimal design. Design should be based on the highest end-of-life options, accounting for separation, purification and degradation.
2. Maximize atom circulation. Circular processes should aim to maximize the utility of all atoms in existing molecules.	8. Assess sustainability. Environmental assessments (typified by life cycle assessment) should become prevalent to identify inefficiencies in chemical processes.
3. Optimize resource efficiency. Resource conservation should be targeted, promoting reuse and preserving finite feedstocks.	9. Apply ladder of circularity. The end- of-life options for a product should strive for the highest possibilities on the ladder of circularity.
4. Strive for energy persistence. Energy efficiency should be maximized.	10. Sell service, not product. Producers should employ service-based business models such as chemical leasing, promoting efficiency over production rate.
5. Enhance process efficiency. Innovations should continuously improve in- and post-process reuse and recycling, preferably on-site.	11. Reject lock-in. Business and regulatory environment should be flexible to allow the implementation of innovations.
6. No out-of-plant toxicity. Chemical processes should not release any toxic compounds into the environment.	12. Unify industry and provide coherent policy framework. The industry and policy should be unified to create an optimal environment to enable circularity in chemical processes.

Sustainable Chemistry

The OECD has defined[67] ‘sustainable chemistry’ as *“a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. Sustainable chemistry encompasses the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes."*

Sustainable chemistry is a broader field[68] that includes ‘green chemistry’.[69] It adopts systems thinking and cross disciplinary approaches, as advocated in **‘**one-world’ chemistry[59], and new business models to encompass the entire life cycle of materials and reduce the use of all resources and materials flows. To achieve this, Kümmerer[70] has pointed out that:

> substance, material, and product flows should be as homogeneous as possible, and should also be of low spatial and temporal scales and with low dynamics. The more heterogeneous such flows are, the more energy and technological processes are needed to separate the components again. New products generally contain more new components than older ones. If innovation cycles are becoming shorter, or the concentrations or total amounts of specific constituents are too low, it becomes increasingly challenging to adapt or develop appropriate treatment and recycling technologies.
>
> All stakeholders, and especially chemists, should therefore initially ask themselves if nonchemical alternatives for a specifically required function or service are possible and if they are more sustainable. Only if a thorough analysis shows that a chemical solution will be needed, should we then assess which chemical product can deliver the required function and service in the most sustainable manner over its entire lifecycle in the given context. Reduction as a goal for chemical products is a guarantee the sustainable use of resources, technology, and products and is a recipe for the safe future of chemistry.
>
> This new self-understanding is a hallmark of a sustainable chemistry and key to a true sustainable contribution of chemistry to the challenges ahead, thereby securing its own future viability. At the same time, it is the biggest challenge, as our self-understanding as chemists is based on the creation of ever-new chemicals and materials.

COMMON THREADS

Key linkages in concepts and approaches can be identified among all the above global sustainability agendas and chemistry-based approaches:

- It is evident than none of the problems of sustainability can be solved without major inputs from chemistry, which provides (a) understanding of the ‘molecular basis of sustainability’ (a term used by Anastas and Zimmerman[71]); (b) potential routes to solutions through prevention, mitigation, clean-up, etc.
- All the approaches recognize the interdependence and interconnections between human activity in the Anthropocene (including the practice of chemistry), human and animal health and the biological and physical environments of the planet. This recognition requires that any potential chemistry activity must be considered in the context of its possible impact on these interlocking environments and Aarth and societal systems.
- Consequently, a systems approach is essential – ***systems thinking can be seen as the thread that runs through, and unites all these approaches to sustainability***.

The IOCD action group, ***Chemists for Sustainability*** (C4S)[72] has been working in the last few years to promote sustainable development, highlight the indispensable roles that the chemical sciences must play, and defend the scientific approach against movements that undermine public trust in science.

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