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Chemical Sciences in Development

The Chemical Sciences and a Sustainable Future

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Abstract

The chemical sciences have been central to global progress, for example contributing substantially to improvements in wealth and health during the last two centuries. They will be essential to meeting oncoming global challenges – especially sustainable development. However, to make its optimal contribution, chemistry must make some deep-seated adjustments to its mission, education and practice. 'One-world chemistry' offers a framework for reorientation and for the adoption of systems thinking and cross-disciplinarity.

Chemistry has been of fundamental importance to development, economic growth and well-being for centuries. It must now play a central role in ensuring a sustainable future for our planet.

If we look back to ancient civilizations like Egypt and China, we find evidence that the precursors of modern chemists, the alchemists, were already experimenting with matter and trying to transform it. Islamic[1] and European alchemists of the Middle Ages took up these efforts

The alchemists had two major goals in their work: they were searching for the Philosopher's Stone, a substance that would transform base metals into precious ones like gold and silver; and they were also searching for an Elixir that would confer eternal life or eternal youth on the person who drank it. The alchemists were not at all successful in their quest, but their efforts did occasional have some interesting results – as when, in the search for the Philosopher's Stone, the distillation of urine led to the discovery of phosphorus; or when Chinese alchemists blending substances to try to create the Elixir of Life invented gunpowder.

But if the alchemists were not successful in trying to create wealth or extend the human lifespan, in the modern age their scientific successors have been spectacularly successful and the chemical sciences have played a central role in this success.

Let's look at how human wealth has changed over time. A graph plotting average global Gross Domestic Product per capita (Gross World Product/capita), expressed in constant dollars, over the last 2000 years shows that global GDP per capita remained relatively unchanged for over the first three quarters of this whole period of two millennia, but then began to rise increasingly steeply.

An important precursor to the steep rise in GDP/capita was the Agricultural Revolution, which took place in the 17-19th centuries in Europe. By greatly increasing agricultural output, it liberated large numbers of people from the business of growing food and they flocked to the towns and cities, where the industrial revolution was able to benefit from their labour.

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a. This article is based on the TGH Jones Memorial Lecture presented by Stephen Matlin at the University of Queensland, 16 July 2018.

The chemical sciences made a major contribution to this growing global wealth:[3]

- Since 1800, the field of electrochemistry laid the foundations for the electrochemical industry, including the generation of electrical power, its storage in portable forms in batteries, and electrolysis processes providing valuable industrial materials.
- Synthetic chemistry began making big advances in the 1840s and 50s with work on the aniline dyes. As well as directly stimulating new fashion industries, the expertise that began to accumulate in the scale-up and commercialization of synthesis processes very soon led to major growth in organic chemicals industries.
- The foundations of biochemistry were laid in the 1860s and paved the way for the development of the biotechnology industry.
- From the 1830s to the 1930s, work on polymer chemistry created a new set of industries manufacturing materials such as rubbers, fibres, polymers and plastics.
- Studies on the first synthetic drugs around 1900 created many of the basic principles of medicinal chemistry and gave rise to the modern pharmaceutical industry.
- The development of spectroscopy and chromatography provided the basis of analytical sciences with applications including food, medicine and the environment.
- The second agricultural revolution had its origins in work in the early 20th century on nitrogen fixation and later on the insecticidal properties of DDT. These were precursors to a wide range of agrochemical industry products.
- The demonstration of the first semiconductor effect in 1833 and work over a century later on semiconductors and transistors were important milestones in solid state chemistry. We are currently witnessing an ever-expanding range of applications of solid state display devices and microchips that are transforming our lives.

Overall, current gross world product is something in the region of US$ 80 trillion per year (which is over $100 trillion Australian dollars/year). It’s difficult to exactly quantify the total contribution of the chemical sciences to this sum, but it’s clearly very large – globally, the bulk chemicals sector alone is worth over US$5 trillion; the pharmaceutical industry alone contributed over US$1 trillion in 2016; and the global agrochemical industry contributes over US$ 200 billion per year to the global economy.

And chemistry – especially solid-state chemistry – plays a hugely important role in many aspects of the ICT industries. Just to take one aspect of that – the global market for Smartphones was worth more than US4 430 billion in 2016 and chemistry is fundamental to the performance of many of its high-tech components, including the electronics, the battery, the screen and the casing.

Of course, the huge rise in global GDP per capita during the last couple of centuries has not been evenly distributed around the world. Looking at a global map of income distribution, as measured by GDP per capita,[2] we find that average country incomes vary by one to two orders of magnitude, across the range of high-, middle- and low-income countries.

To take a couple of examples of the direct role that chemistry has played in economic development at the national level:

- Belgium is a high-income country, with a current GDP per capita of over US$40,000. A large part of Belgium’s economic and industrial development since the 19th century can be traced to the chemical industry and life sciences, which currently account for around a quarter of the total manufacturing sector.[3]
- Taiwan provides an example of a HIC country (with a current GDP per capita over US$ 20,000) which transformed its economy during the second half of the 20th century, with national planning and investment in chemistry capacity playing a key role. Between the 1950s and 1990s, Taiwan’s per capita GDP rose eight-fold to over US$ 7,000 (for comparison, Australia’s GDP per capita rose about 2½ - fold during that time) and in the 1990s the chemical industry was Taiwan’s largest industrial sector, contributing a quarter of the total production value. As well as technical and strategic factors, there was a crucial political component to Taiwan’s success in the chemical

industry sector – there was strong support by the government, including well-planned industrial zones and tax, investment and export incentives.[4]

In the case of Australia, the chemistry contribution is not so large, but around 75,000 people are employed in chemicals and plastics manufacturing; and a similar number in the life sciences, which includes the major area of pharmaceuticals.

So, it's fair to make the claim that "the chemical sciences have been central to global progress", for example in the area of wealth creation. But before going further, there's a general point to make:

People promoting the field of chemistry often like to focus on just one side of the coin and to emphasise the global 'goods'. They like to say ***"Look at all the great things that chemistry has done for us!"*** An example is the slogan that the DuPont chemical company used 1935-1982: *"Better things for better living… through chemistry"*,[5] which was subsequently contracted to *"Better living through chemistry"*. But where there are 'goods' there can be 'bads' as well: so, for example, increasing wealth over the last few centuries has been associated with increasing pollution of the environment; the development of new pharmaceuticals and agrochemicals has been intended to give us better health and nutrition, but it's sometimes led to severe problems of toxicity for human beings and animals. And when faced with the bad side of the coin, the temptation for those who promote chemistry is to try to ignore it and just say that '*The bad things are the fault of people, not of chemistry!'*

When talking about chemistry, it is very important to openly acknowledge three things:

- All chemistry knowledge can be applied for good or bad: it's people in every part of society, (including scientists, policy-makers and the public) who decide;
- Chemistry literacy is about acquiring the capacity to make informed choices;
- All choices have implications beyond the immediate setting – which means that chemistry literacy must be taught in the context of real-world applications

And every day in the world around us we can see the need for chemistry literacy in society if people are to have the capacity to make informed choices. You can try this chemistry experiment for yourself: type the words 'chemical-free product' into Google – in less than half a second Google will find you about 300 million references. So what kind of chemistry literacy are we providing in our schools that leaves people thinking that this is possible? The Royal Society of Chemistry has had its doubts about these claims – in 2010 it issued an offer of a £1 million bounty for anyone who could deliver a chemical-free product, after a survey by the cosmetics and toiletries industry showed that half of women and over a third of men were seeking chemical-free products.

Well, having made the case that the chemical sciences have been central to global progress, I now want to add that they will be essential to meeting oncoming global challenges, especially sustainable development.

And I want to make the case that, to make its optimal contribution, chemistry must change, and to argue that 'one-world chemistry' offers a framework. I will explain that framework and provide some examples to show how systems thinking might be valuable in chemistry education and practice.

Let start, however, by emphasising that the new chemistry that we are advocating is not intended to replace our existing chemistry, but rather to build on it by extending the scope of our attention.

If we think about the nature of chemistry, it's clear that it has been strikingly successful in playing three roles.

1. As a core physical science that helps us understand the properties and behaviour of atoms and molecules and the transformation of substances.
2. Providing useful applications: The 19th century French chemist Marcellin Berthelot (1827 – 1907) observed that *"chemistry creates its own object"*, by simultaneously studying matter and achieving its transformations.

3. Chemistry has been – and remains – a very successful platform science – fundamental to the development of a range of other 'molecular sciences' which depend on knowledge of the properties, behaviour and transformations of atoms and molecules, including: Biochemistry, Molecular biology, Materials science, Nanoscience, Medicine, Food production, Structural & functional materials, Energy & Fuels, Information & communication technologies, etc.

But if we ask the question "what's the purpose of chemistry?" some of us would argue that, in addition to these 3 roles, we need to add a 4th one that is vitally important in the 21st century – that chemistry needs to be "a science for the benefit of society", a science that helps to meet oncoming global challenges.

What are these 'oncoming global challenges' that I have referred to? There has been no shortage of analyses in recent years.

For example, the third Copenhagen Consensus[6] emerged from a meeting in 2012 of a panel of experts (all economists and including 4 Nobel Prize winners). They produced a list of 10 of the world's biggest challenges, with recommendations on how to tackle them: the results were published in a book entitled *"How to Spend $75 Billion To Make The World A Better Place"*.[7]

Specifically in the field of chemistry: about 10 years ago the Royal Society of Chemistry and American Chemical Society agreed to collaborate in meeting the coming global challenges. In 2009, the American Chemical Society published a major study on global challenges and how chemistry could contribute to solutions.[8] The report highlighted a number of priority areas and these converge with the issues in the Copenhagen Consensus.

In parallel, a report in 2009 by the RSC on 'chemistry for tomorrow's world' highlighted 7 priority areas where chemistry can contribute. Note that both the ACS and RSC reports referred to 'sustainability' as one of the big challenges – and indeed this has emerged as the most serious overarching challenge for the whole planet in recent decades.

A useful concept that has been developed in the last 10 years or so is that of Planetary Boundaries (PBs). This idea has been developed by the environmental scientist Johan Rockström in Sweden, the chemist Will Steffen at the Australian National University, and others.

For more than 10,000 years, since the last great Ice Age, humanity has enjoyed a relatively stable planetary epoch known as the Holocene, which has provided relatively benign conditions that have been beneficial to the global population. However, human actions since the Industrial Revolution have become the main driver of global environmental change and the Holocene has given way to a new epoch now termed the Anthropocene.

Rockström, Steffen and their colleagues have identified 9 Earth system processes which have boundaries. These are 9 critical areas where, once certain thresholds or tipping points are passed, there is a risk of "irreversible and abrupt environmental change". They have used these to define a "safe operating space for humanity". We will return to look at one of these boundaries – that for nitrogen – shortly.

The idea of sustainability has evolved since the 1970s. The concept of 'sustainability' was first used in its current sense in a report entitled 'The Limits to Growth' published in 1972 by the Club of Rome (an influential international think-tank). It recognized the danger that the world was consuming resources at an increasing level that could not be supported in the future. In the 1980s the UN established a World Commission on Sustainable Development chaired by Gro Harlem Brundtland (who at various times was Prime Minister of Norway and Director-General of WHO). Their 1987 report defined Sustainable Development as "***Development that meets the needs of the present without compromising the ability of future generations to meet their own needs".*** The need for sustainability was further highlighted in the 1992 Earth Summit in Rio de Janeiro, and the 'Agenda 21' document from this conference was

subsequently developed further as a manifesto for "socially inclusive and environmentally sustainable economic growth". And on the 20th anniversary of the Rio conference, 192 governments renewed their political commitment to sustainable development in a document entitled "The Future We Want".
… and culminated in the formulation of 17 Sustainable Development Goals (SDGs) which were adopted by all 193 UN Member States in 2015.

The 17 SDGs are constructed on a concept of shared responsibility by all governments in the world and contain a central principle of "leaving no-one behind".

If you take these and other similar lists and try to boil them down to the essentials, they reflect a combination of aspirations for progress and determination to deal with some looming crises. There seem to be at least three major sets of inter-related crises that our planet is facing in the 21st century:

- First, there are challenges to our planetary systems. Symptoms of these evolving crises include the well-documented observations of:
    - Climate change
    - Atmospheric pollution
    - Land degradation
    - Ocean contamination

Second, there is the area of health, where we see challenges due to the fact we have a growing world population that is increasingly urbanizing and ageing. There are challenges due to the emergence of new diseases[9],[10] and at the same time old diseases like TB that we thought we had conquered have re-emerged as major health problems. And the traditional model of drug development, which seemed to have served us so well in the last century and a half, is now failing in some important respects.

The third area of crisis relates to the fact that we're seeing the prospect of serious shortages in many key resources, including food, water, energy and materials – and the environment itself is now understood to be another resource with finite limits.

Alongside these three sets of crises, there are two further sets of issues that are cross-cutting:[11] it's a dirty world, in which pollution of land, sea and air is harming the entire biosphere; and it's a fake world, in which counterfeiting and adulteration are very widespread and, among other areas, affect food, medicine and the environment.

My point today is that, clearly, there are many ways in which the chemical sciences can contribute to solutions to these problems. But as we start to look at the contributions that the chemical sciences can make, I want to emphasize that the nature of the challenges has three aspects: there are not just challenges for the specific science content needed to solve particular problems; but also for developing the capacity for science and in the governance of science.

About 4-5 years ago, a group of us associated with the International Organization for Chemical Sciences in Development began working and thinking together and writing a series of articles about the future of chemistry – especially in the context of sustainability. One of our articles, published in Nature Chemistry in 2015, discussed the need for chemistry to make pivotal contributions to help realize the ambitious Sustainable Development Goals. But we argued that, to do so, chemistry needs a new orientation in its priorities, approaches and practices.

We followed this up with a paper in 2016 in which we proposed what this new orientation might be – which we called 'one-world chemistry' and which offers a framework for how to achieve this reform.

In its orientation, 'One-world chemistry' (OWC) aims to be a science for the benefit of society, governed by ethical practice, infused with systems thinking and embracing cross-disciplinary approaches.

OWC recognises that the Earth is a single system in which the health of human beings, animals and the environment are all strongly interconnected: and consequently that all three must be taken into account in considering the impacts of chemistry.

The OWC approach has implications for chemistry education: it reflects a clear, 21st Century idea of **what chemistry is about**; it emphasises learning chemistry in the **context of its applications** AND in the **context of its impacts**. To do so, it requires thinking about systems and how they function and interact; and it also requires **connecting science principles with sustainability goals.**

Let's unpack the terms system and systems thinking a little bit. A system can be defined as an interconnected set of elements that is coherently organized in a way to achieve a function or purpose. Systems thinking refers to a way of using strategies to develop understanding of the interdependent components within and among complex, dynamic systems.

It's about seeing and understanding systems as wholes rather than as collections of parts, – as a web of interconnections that creates emerging patterns which help to identify the leverage points that lead to desired outcomes.

Let's take a concrete historical example which has a clear contemporary resonance.

If we are learning about the synthesis of the alkyl halides, we would cover things like free radical and ionic substitution and addition reactions and we would consider the properties of the halogen elements and how these affect the physical and chemical properties of the organic halides. A broader chemistry literacy requires that we ask how these substances fit in the real world and what kinds of roles people play in determining their use. There are many examples that could be chosen of well-known applications of organic halides, including those listed here: let's briefly consider the case of refrigerants – and, in particular, of the fluorocarbons.

The thermal effects of gas expansion and of liquid evaporation provide textbook examples of the physical basis for refrigerators, but the search for the ideal chemicals to use as refrigerants has been a continuing challenge. Early refrigerants like ammonia were tried, but were found to be too toxic and corrosive for domestic use. This General Motors 'Monitor Top' domestic refrigerator from about 1927 used sulphur dioxide, but this was also corrosive and tended to leak, with results that were both smelly and very toxic. Methyl chloride was also tried, but was toxic and also extremely flammable.

Seeking less dangerous refrigerants, in 1928 Thomas Midgley, working at General Motors, improved the synthesis of chlorofluorocarbons (CFCs) such as CF_2Cl_2 (b.pt. -30ºC). This was patented by GM and developed by Kinetic Chemicals as 'Freon'. It was used in refrigerators from 1930; and by the 1960s members of this family of halogenated fluoroalkanes or 'halons' were also being widely used as propellants in aerosol cans and in fire-fighting as well as refrigeration, as they are non-flammable.

The electron capture detector, invented by James Lovelock in 1957, is extremely sensitive for the detection of halogenated compounds in gas chromatography. In the late 1960s, Lovelock was the first person to detect the widespread presence of CFCs in the atmosphere and it was subsequently shown that these chemically inert gases accumulate in the stratosphere and have very long lifetimes there.

Alarm bells rang in 1974, when Molina and Rowland (who subsequently shared the Nobel Prize) published their findings that the photolysis of atmospheric CFCs by sunlight releases chlorine atoms and these catalyse the breakdown of ozone. It's been shown that since the 1970s there's been a steady decline in atmospheric ozone. A particularly large annual springtime decrease in stratospheric ozone over the southern polar region was discovered in the mid-1980s by the British Antarctic Survey. This is the so-called 'ozone hole', which has continued to grow into the 21st century. [12,13,14]

Following the publication by Molina and Rowland, there was immediate public concern which focused both on the environmental damage itself and on the attendant increased risks of skin cancer. Here the interaction of chemistry, biology and environmental systems had reached a crisis point and public opinion demanded immediate, global action.

In 1977 the UN Environment Programme (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. The Vienna Convention,[15] concluded in 1985, was a framework agreement in which States agreed to cooperate to understand the ozone problem, and to adopt "appropriate measures" to prevent activities that harm the ozone layer. The obligations were general, however, and contained no specific limits on chemicals that deplete the ozone layer. These came two years later, in 1987, as an addition to the Vienna Convention, when the Montreal Protocol on Substances that Deplete the Ozone Layer[16] was signed. This protocol required the rapid phasing out of CFCs and a slower phasing out by 2030 of hydrochlorofluorocarbons (HCFCs), which are less damaging to the ozone layer but are also very powerful greenhouse gases.

It was remarkable that international agreement should be reached so quickly on such a major and contentious issue. Richard Benedick, who headed the US delegation in the ozone negotiations, commented[17] 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 that originated with chemistry.

There are a number of strategies & tools already in use that can assist in introducing systems thinking in chemistry education

- Learning from rich contexts
  http://pubs.acs.org/doi/abs/10.1021/sc500415k
- Case-based learning
- Problem-based learning
- Next Generation Science Standards –3D learning
  www.nextgenscience.org
- Cross-cutting and cross-disciplinary concepts*
  Bringing together knowledge, methods, tools from different disciplines
- Chemical thinking learning progressions
  Describes likely pathways in the evolution of students' chemical thinking with training in the discipline. Sevian & Talanquer CERP 2014, 15, 10-23
- Life cycle analysis
  Understanding product life cycle concepts has fundamental value to students

Life cycle analysis: Consider the life cycle of a chemical product:

- Chemical reactions, whether they are small-scale laboratory or large-scale manufacturing processes, generate waste materials that need to be managed – including containment, disposal and recycling – in a safe and sustainable manner.
- The raw materials used, whether they are natural resources or other manufactured intermediates, must be sourced efficiently, cleanly, safely and sustainably.
- The products of manufacture may find very diverse uses, including household, medical, industrial and agricultural applications in which they come into contact with people, animals and the environment – and they must therefore be tested to ensure their biological and environmental safety.
- After use, the products or their consequent waste must be disposed of or recycled efficiently, cleanly, safely and sustainably.
- At every stage, the chemistry system in which the product is manufactured, used and disposed of is interacting with the human system. Actions involving chemistry don't just 'happen': they occur because of decisions that people take, individually or collectively. These decisions may result from diverse human motivations, including curiosity and aspirations for success, wealth, power or pleasure; and they are influenced by legal constraints, by societal pressures and by movements for the advance of collective local and global goals.

- The chemistry system therefore interlinks with a host of other overlapping systems including the biosphere, the environment, human and animal health, economics, politics, psychology and the law.
- A useful starting point is the adoption of green chemistry principles.

Green Chemistry: 20 years ago, Anastas and Warner put forward 12 Green Chemistry Principles which cover the design and application of chemical products and processes that reduce or eliminate the use and generation of hazardous substances.[18] A review of progress with the application of these principles has just been published in the RSC journal 'Green Chemistry'.[19]

The importance of this term design was highlighted a couple of years ago in a paper by the chemist Paul Anastas and engineer Julie Zimmermann, in which they talked about the 'molecular basis of sustainability'.[20] They emphasized that defining green chemistry through design amounted to a paradigm shift, in which chemists could plead ignorance of to the consequences of their science, but must accept their ultimate responsibility for consequences that flowed from the design. The linkage to fundamental chemistry was illustrated through a series of examples of questions about chemical bonding, such as the consequences of the nature of particular chemical bonds for our current energy systems, for stratospheric ozone, for toxicity and for global climate change.

This kind of approach helps to demonstrate how many of our environmental concerns are derived from molecular characteristics, and leads to the understanding that many of the solutions are, potentially, also molecular.

Let's return to the Planetary Boundaries idea and I would like to explore it using the example of Nitrogen to show how systems thinking can be applied.

The planetary boundary for N was set at 62 Teragrams/year (62×10^{12} g/y)of industrial and intentional N fixation, with a zone of uncertainty extending out to 82 Teragrams/year. The actual production level at the present time is estimated to be around 150 Teragrams of nitrogen per year.

So how does this look from a chemistry perspective?

What was, arguably, the most important technological invention of the 20th Century? The Haber-Bosch Process for production of ammonia from nitrogen and hydrogen. Smil calculated in 1990 that 40% of the world's population would not be fed without the impact of nitrogen fertilizers on agricultural production.

But while this is clearly a major contribution to keeping the world fed, has there also been a failure of systems thinking? In a vegetarian diet, 86% of the N coming from fertilizers is lost in crop production – and the loss rises to 96% in the production of meat.

Let's have a brief look at how we can use systems thinking to explore and understand what is happening. I would like to briefly refer to some new materials that we have been working on with Peter Mahaffy and Tom Holme, as part of a joint IUPAC-IOCD project on infusing systems thinking into chemistry education.

We can start with a sub-system which describes the core reaction – the Haber-Bosch process for producing ammonia. Very often, in a chemistry course, that will be extended to look at the sub-system responsible for controlling the reaction, which depends on the catalyst and the need for high temperature and pressure to drive the equilibrium reaction according to Le Chatelier's Principle. The chemistry course might also consider the chemical inputs sub-system, asking where the raw materials come from; the energy inputs sub-system which asks how the high temperature and pressure are generated and the role of hydrocarbon fuels in also sourcing methane from which the hydrogen is derived; and, beyond the synthesis of ammonia, the course may consider how ammonia is oxidised in the Oswald reaction to produce nitric acid, which combines with ammonia to provide the ammonium nitrate use in producing nitrogen fertilizer.

All of these sub-systems relate directly to the chemistry that creates ammonium nitrate and this illustrates the value of using a systems approach and tools to help the student organise and make sense of the chemistry. Chemistry courses are very like to stop there, but if we want to place nitrogen fertilizers in the real world, we would go on to look at the intended uses, which include not only agriculture and the effects of nitrogen in the environment, but also the synthesis of explosives[21,22] which have had massive uses in warfare as well as peaceful uses in mining and construction. We might also go on to look at unintended consequences, such as impacts of environmental sources of reactive nitrogen on health.

The systemigram is valuable tool for mapping out these relationships. It can also be the starting point for thinking about how to modify systems and what the consequences might be. For example, we could ask about:

- The consequences of finding alternative sources of the key raw materials
- Or of different sources of energy
- Or what happens if we find completely different ways of making ammonia (for example, a great deal of work is being done on the electrochemical synthesis of ammonia)
- Or even more radically, of finding biological ways of fixing nitrogen using microorganisms, to bypass the entire chemistry synthesis system.

This also helps to relate the system to global challenges such as planetary boundaries or the connections between the nitrogen biogeochemical system and the Sustainable Development Goals

Peter Mahaffy and I are currently co-directing a project[23] of the International Union of Pure and Applied Chemistry, that is co-supported by IOCD. We have a team of over 20 leading chemistry educators from around the world involved with us in developing the use of systems thinking in chemistry education.

Acknowledgements

I thank the University of Queensland for the invitation to give the TGH Jones Memorial Lecture in 2018, the International Organization for Chemical Sciences in Development for support to visit Australia and Peter Mahaffy, Tom Holme and Jennifer MacKellar for collaboration in the project on systems thinking in chemistry education.

References

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[1] Chemistry and alchemy
http://www.grouporigin.com/clients/qatarfoundation/chapter2_3.htm
Chemistry in the Arab World
https://www.learner.org/courses/chemistry/text/text.html?dis=U&num=Ym5WdElUQS9NaW89&sec=YzJWaklUQS9OQ289

[2] Country Income Groups. Washington DC: World Bank, July 2011.
http://chartsbin.com/view/2438

[3] Key facts. Belgian Federation for Chemistry and Life Sciences Industries, 2015.www.essenscia.be

[4] Y.-C. Hu, S.-C. Chen. Taiwan's chemical industry: Looking back and looking ahead. CEP Magazine, April 2012, 41-46. www.aiche.org/sites/default/files/cep/20120441.pdf

[5] MillMatt. *Modern Living Through Chemistry? Electronics? Agriculture?* IHS Engineering360, 10 August 2013.
http://cr4.globalspec.com/blogentry/23132/Modern-Living-Through-Chemistry-Electronics-Agriculture

[6] The Third Copenhagen Consensus. Copenhagen Consensus Center, 2012.
www.copenhagenconsensus.com/copenhagen-consensus-iii/research

[7] B. Lomborg. *How to Spend $75 Billion To Make The World A Better Place*. Copenhagen Consensus Center, 2014.
www.copenhagenconsensus.com/copenhagen-consensus-2012/how-spend-75-billion-make-world-better-place

[8] Global Challenges/Chemistry Solutions. Washington DC: American Chemical Society, 2009, 84pp.
www.cendigital.org/acsgccs/2009#pg1

[9] C. Turkington, B.L. Ashby. Encyclopaedia of Infectious Diseases, 3rd Edn, 2007, xiii.

[10] K. E. Jones et al. Global trends in emerging infectious diseases. Nature 2008, 451, 990-993.
www.nature.com/nature/journal/v451/n7181/full/nature06536.html#close

[11] S. A. Matlin. Keynote Paper at the *23rd International Symposium on Pharmaceutical and Biomedical Analysis (23PBA)*, João Pessoa, Brazil, 9-12 October 2011. http://www.iocd.org/v2_PDF/371-2011pba23-1-13.pdf

[12] R. McKie. The Guardian 18 April 2015.

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www.theguardian.com/environment/2015/apr/18/scientist-who-discovered-hole-in-ozone-layer-warns

[13] www.theguardian.com/environment/2014/oct/31/ozone-hole-layer-remains-size-of-north-america-nasa-data-shows

[14] Depletion of the Ozone Layer. Chemistry LibreTexts, 30 September 2014. https://chem.libretexts.org/Core/Physical_and_Theoretical_Chemistry/Kinetics/Case_Studies%3A_Kinetics/Depletion_of_the_Ozone_Layer

[15] Vienna Convention. http://legal.un.org/avl/ha/vcpol/vcpol.html

[16] Montreal Protocol on Substances that Deplete the Ozone Layer. http://en.wikipedia.org/wiki/Montreal_Protocol

[17] R.E. Benedick. Science, diplomacy, and the Montreal Protocol. The Encyclopeadia of Earth. www.eoearth.org/view/article/155895/

[18] P. Anastas, J. Warner. Green Chemistry: Theory and Practice. New York, Oxford University Press: 1998

[19] H. C. Erythropel, et al. ***Green Chem.***, 2018,**20**, 1929-1961. https://doi.org/10.1039/c8gc00482j

[20] P. Anastas, J. B. Zimmerman. The Molecular Basis of Sustainability. Chem 2016, 1, 10-12. https://www.cell.com/chem/fulltext/S2451-9294(16)30020-1

[21] L. Y. Stein, M.G. Klotz,. *The nitrogen cycle*, Current Biology 2016, 26, R83–R101.

[22] J. W. Erisman, M. A. Sutton, J. Galloway, Z. Klimont, W. Winiwarter, Century of ammonia synthesis, Nature GeoScience, 2008, 1, 836 – 839.

[23] Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education. IUPAC Project No. 2017-010-1-050. International Union of Pure and Applied Chemistry, Research Triangle Park, NC 2017. https://iupac.org/projects/project-details/?project_nr=2017-010-1-050