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Chemistry for the sustainability of people and planet: Why chemists need systems thinking

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This talk is about the critically important role that chemistry plays in helping meet oncoming global challenges such as pandemics, climate change and other threats to the health and wellbeing of people and the sustainability of the planetary environment that we inhabit. It also aims to explain what systems thinking is about and why chemists need it. It will focus, in particular, on work which has been done by our group of 'Chemists for Sustainability' at the International Organization for Chemical Sciences in Development (IOCD).

Looking back to ancient times, in many different parts of the world there is evidence that the alchemists, who were the precursors of modern chemists, were already experimenting with matter and trying to transform it. 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. Of course, no-one succeeded in doing this, but along the way the equipment for handling chemical reactions developed and one of the outcomes of alchemists' experiments was the discovery of white phosphorus from the distillation of urine. As well as seeking wealth, the alchemists were also searching for an Elixir that would confer eternal life or eternal youth on the person who drank it. This was again a failure, but gunpowder was probably invented by Chinese alchemists blending substances to try to create the Elixir of Life.

If the alchemists were not able to create wealth or extend the human lifespan, in the modern age, the chemical scientists to which they gave way have been spectacularly successful, both in creating new knowledge and in finding useful applications. In particular, the chemical sciences have played central roles in contributing to wealth and health.

Let's look at how overall human ***wealth*** has changed over time. Tracing average global Gross Domestic Product per capita, expressed in constant dollars, over the last 2000 years, it can be seen that global GDP per capita remained pretty constant until just a couple of hundred years ago, but then began to rise increasingly steeply. As the science of transformation of matter, chemistry has played fundamental roles in this growing global wealth, including laying the foundations for industries based on electrochemistry, synthetic and medicinal chemistry, agrochemistry and biotechnology, polymers and plastics, and semiconductors and transistors.

Turning now to ***health***, was there not some golden age, before human beings began the industrial development of the planet, when people lived healthy, clean and long lives close to nature? No, actually: at the dawn of human history, average global life expectancy was less than thirty years – and remained below this level until the second half of the 19th century. It then began to increase very rapidly and more than doubled during the 20th century. Over the past 150 years, average global life expectancy at birth has increased by roughly 3 months per year.

Chemistry's contributions to this dramatic increase have included knowledge that has supported better public health in areas such as water quality and nutrition, as well as providing anaesthetics and pain killers that revolutionised surgery and dentistry, and a host of drugs for treating diseases including antibiotics, anticancer and antiviral agents, and treatments for mental and neurological disorders. It is estimated that antibiotics alone contributed, on average, 23 years of additional life span to human beings during the 20th Century.

Of course, neither average wealth nor average life expectancy are evenly distributed around the world, either between or within different countries. National average life expectancies for some countries now exceed 80 years, while for others, national average life expectancies can be as low as half that - including for some of the poorest countries such as those in parts of Africa.

Looking in detail at the sources of the improvements that have been made in life expectancy and other measures of human health – and the reasons why these can vary so much from place to place – it is evident that at least three kinds of factors are involved and are closely intertwined. Two of the factors are technological in origin, with prominent roles being played by the chemical and biological sciences. The third factor consists of the so-called 'social determinants' of health, which includes a wide range of economic, environmental, political and social determinants.

These different kinds of factors are all important when we come to look more broadly at the oncoming global challenges in the 21st Century. Some of these challenges concern the state of the body and the need for effective diagnosis, prevention and treatment of a very wide range of diseases, including old, new and re-emerging diseases, epidemics and pandemics, non-communicable diseases such as cancer, diabetes, stroke and heart disease, and so-on. And many of the challenges concern the state of the world, including the global environment and economic, political and social factors. To address these challenges, we need always to set them in the context of what is sustainable for both people and the planet.

To address this large and daunting list of areas, how are chemists to make choices about where they might apply their knowledge and skills to help meet the global challenges? There are a number of frameworks that can help to guide us, to help direct our attention in making these choices and also guide as to what needs to be done and what would not be helpful approaches. In particular, three frameworks seem to be particularly worth exploring from the chemist's perspective:

1. UN Sustainable Development Goals
2. Planetary Boundaries
3. Human Security

Of these three, the United Nations Sustainable Development Goals are probably the most familiar to chemists. They provide a set of 17 goals which set milestones, mostly to be achieved by 2030, that are considered important stages on the road to sustainable development. When the goals were agreed at the UN in 2015, our group of 'Chemists for Sustainability' published an article in which we pointed to the many ways that chemistry could and should contribute to achieving them.

But we also recognized that, to make its most effective, optimum contribution, chemistry itself would need to change. And in a follow-up paper we set out one possible direction for this change, which we called 'one-world' chemistry. This recognizes that human and animal health and the environment are all intimately inter-connected systems; 'one-world' chemistry aims to be a science for the benefit of society; and it requires that chemists adopt systems thinking and cross-disciplinary approaches.

Systems thinking has been identified as one of several key competencies that are essential for achieving sustainability. This competence is the ability to analyse complex systems across different domains and across different scales. Let's clarify what is meant by 'systems'. A system is a set of components, working together to form a complex whole that produces a function. Systems have boundaries and properties –typical properties of importance being that systems change over time and this capacity to be dynamic means that they can produce a function which emerges from the working of the system. So, for example, the system can be an object such as a clock that tells the time or an organism that lives; or the system can be a process such as an organization's management system or a regulatory system to ensure the quality of a product.

In all these cases we see the emergence of the function from the working of the whole system. It is apparent that the overall function or effect does not come from the isolated parts separately, so, for example, time-telling is not a property of individual cogs and springs in a clock; life is not a property of individual molecules in a cell. This aspect of systems is of particular relevance when we come to talk about sustainability because sustainability is a property of the whole system – it is not simply a property of individual elements of the system.

Let's look at a typical system that has chemistry at its core: a reaction between reagents A and B that leads to products C and D. This reaction takes place in the presence of particular solvents, reagents and catalysts, and under particular physical conditions such as defined temperature, pressure, degree of agitation, and so on. What takes place in the reaction vessel can be described as a reaction system that produces a particular chemical result. But this system could not operate without inputs of various kinds and we need to ask "where did the starting reagents A and B come from, where did the solvents, reagents and catalysts come from and how were the physical conditions of the reaction generated?" So, we need to be concerned with the supply systems for materials and energy. We also need to ask about what happens to the solvents, reagents and catalysts during and after the reaction. Are they reused, repurposed or scrapped? This means that we must ask questions about the disposal systems for both matter and energy coming out of the reaction. If the reaction is used in a manufacturing process, we need to ask about how the main outputs of materials and energy are used and/or disposed of, so we are interested in the application systems; and at the end of the useful life of the products, we need to also pay attention to how they are disposed of.

The disposing of materials is of particular concern when we are focusing on sustainability. We often say that we 'throw things away' after they have been used. But as chemists know very well, matter cannot be created or destroyed but only transformed in its combinations – or as Annie Leonard and Ariane Conrad expressed it, the idea that we can simply throw anything away is a myth: there is no such thing as 'away' – everything must go somewhere.

So, when we look at a production system for any material that is being prepared for use, we need to consider it against this wider background. We need to take a step back and look at the larger picture that examines production and consumption in the context of Earth and societal systems. The production and consumption lead to interactions with the land, atmospheric and aquatic systems, which provide the environment that supports biological systems and their ecological interactions. Moreover, all of these systems are interacting with the human systems of the planet and are influenced by human needs, by the uses we make of materials, by culture and fashion, economics and laws and regulations. When we ask whether a particular human activity is 'sustainable' we need to have all of this picture of system interactions in mind, as we try to decide whether a particular approach is acceptable and at what level of activity it can be sustained without excessively damaging the planetary environment. We need to recall that sustainability is a property of the whole system and not simply a property of individual elements of the system.

One useful viewpoint on the actual level of sustainable activity comes from the Planetary Boundaries approach. Nine Planetary Boundaries (PBs) have been identified that help define the stability and resilience of our planetary environment. So far, control variables have been identified and quantified for seven of these PBs, that indicate whether that Earth system process is still in a safe operating zone (below the PB - green), a zone of increasing risk (yellow), or a zone of high risk (red) as a result of human activity. Most of these control variables are directly related to the production and measurement of chemical substances in the atmosphere, hydrosphere or lithosphere.

By 2015, the control variables for several of these Planetary Boundaries had already exceeded the safe operating zone and were well into the yellow or red zones. The good news, however, is that one of them was actually improving due to international cooperation: the concentration of ozone in the stratosphere had been falling steeply due to the presence of chlorofluorocarbons (CFCs) escaping from refrigeration systems. The banning of these CFCs in the 1987 Montreal Protocol has led to a significant recovery in the ozone coverage, which helps protect us from the harmful effects of UV radiation from the Sun.

It is also important to note that all of these PBs are interactive with one another and a change in the variables in any one can affect all the others. Lets take a specific example, and look at some of the chemistry aspects of climate change. One of the key control variables for the PB for climate change is the concentration of CO_2 in the atmosphere and the boundary level for this was set at 350 ppm. By 2009 the observed level was 387ppm, and it rose to 401 ppm by 2015 and to 412 ppm by 2020. This was the highest concentration of CO_2 seen in the Earth's atmosphere in at least the last 800,000 years, having risen particularly steeply since the mid-20th Century. The last time that such a high level of CO_2 was seen was in the Mid-Pliocene Warm Period, when temperatures were 2°-3°C higher than during the pre-industrial era and the sea level was 15–25 meters higher than today.

To explore where this CO_2 comes from and understand its impacts, we can make use of concept mapping approaches. They are generally constructed by attaching Concept Labels to objects, ideas or effects and then drawing arrows that describe kinds of connections between them. A Concept Map for the biogeochemical flow CO_2 on Earth might begin with the chemistry of the carbon cycle and tracing the origins of CO_2 from both natural metabolism in biological organisms and human activities, most notably the combustion of C-containing materials to produce heat, light and other useful forms of energy. The map can go on to trace how the CO_2 ends up in the atmosphere and dissolved in the oceans, with consequences for the climate and for aquatic and land-based biosystems.

We wanted to develop a more extensive version of the concept mapping approach that would enable us to examine sub-systems and their interactions in more detail. To illustrate how the result of this – the Systems-Oriented Concept Map Extension (SOCME) – can be used, let's look further at the case of CO_2.

The production and release of CO_2 leads to an increasing concentration in the atmosphere. The main sources are the burning of fossil fuels, production of cement for concrete and burning of forests. Some of the CO_2 in the atmosphere dissolves in the oceans, where it is taken up by physical and biological systems and also produces carbonic acid, which damages coral reefs. CO_2 in the atmosphere is also taken up by land systems, including the plant and animal biomes.

Efforts that are needed to mitigate these increases in atmospheric CO_2 include switching to alternative energy sources that are sustainable; capturing CO_2 as it is produced (or, indeed, sequestering it when it is already in the atmosphere), and finding ways to produce greener alternatives to the traditional concrete. CO_2 that has been captured can be an industrial feedstock for synthesis of organic compounds. Chemistry and physics are central to understanding the behaviour of gas molecules in the atmosphere, and provide some of the basic inputs to climate science and the nature of global warming.

Chemistry is also central to some of the approaches to finding alternative, sustainable energy sources. This includes developing efficient ways to trap solar energy and use it in photo-electric devices and photosynthesis. Chemistry is also the key to developing portable energy forms that do not depend on fossil fuels. This includes sustainable batteries based on Li-ions. However, global Li resources are rapidly declining and mining operations create a large carbon footprint. Recent efforts have focused on Li recycling and on the potential for electrochemical Li extraction from seawater. Other metals are being explored as alternative to Li, including : e.g. Al, Mg, Na, Zn. Fuel cells can provide energy via the reaction between H_2 and O_2 in an electrochemical cell – but the H_2 must be made, transported, stored. Alternatively, H_2 can be generated in situ within the fuel cell system by reforming H-rich fuels, e.g. CH_3OH, EtOH, hydrocarbon fuels. It is also possible to use methanol in direct fuel cells: ($CH_3OH + H_2O \rightarrow CO_2 + 6H+ + 6e-$ in electrochemical cell) but the CH_3OH must be made, transported, stored.

Another approach is to employ 'green' fuels for combustion. Hydrogen is one option ($H_2 + O_2 \rightarrow H_2O$ in internal combustion engine), but the H_2 must be made, transported and stored. Moreover, the current synthesis of H_2 is conducted by 'reforming' CH_4 ($CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$) generating CO_2, so 'green' methods are needed for the production of H_2. There are also electrochemical and photochemical options ($2H_2O \rightarrow 2H_2 + O_2$) as well as use of ammonia as a fuel ($4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$ in internal combustion engine), but the NH_3, which is toxic, must be made, transported (usually as liquid at -33°C) and stored. Moreover, the current synthesis of NH_3 generates a large amount of CO_2 its its production also therefore needs 'greening'.

The challenge of how to operate construction sustainably provides another example. Concrete is world's most widely used material for construction. It is an aggregate of sand, gravel, stone bonded together with cement. The making of cement involves CO_2 production ($CaCO_3$ + heat $\rightarrow CaO + CO_2$), which generates 8% of annual global CO_2 emissions. 'Low-carbon' cements are urgently needed, but to date there has been slow progress in this field. Alternatives to concrete are also being explored, such as using waste or residual materials from different industries.

A third framework that can provide guiding principles for chemistry is the Human Security Framework. In 1994, the UN's Human Development Report replaced the traditional interpretation of security as state-centred with a new one in which it was centred on the individual. The human security concept was defined as "freedom from want and fear and freedom to live in dignity" and seven main dimensions of the concept were identified, involving food security, environmental security, economic security, personal security, community security and political security. Among many significant messages for chemists, the concept emphasizes that, while concerned with the material dimensions of human security, chemists must engage with society and policy makers as well.

To summarize, it is evident that the chemical sciences have been good for human progress (e.g. for wealth and health) – but only for some people. The chemical sciences will be essential to meeting oncoming global challenges, and in taking up this objective, chemists can be guided byhe UN Sustainable Development Goals and the Planetary Boundaries and human security frameworks. The biggest overall challenge is achieving sustainability for people and planet and while pursuing this it is vital to recognize that fragmented efforts to 'green' parts of a process are not sufficient. Sustainability is an emergent property of the whole system and not simply of some of its components. Chemists need systems thinking as an essential competence to enable their contributions and must engage not only with many other disciplines but also with society and policy-makers.

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