International Organization
for
Chemical Sciences in Development

The Contribution of the Chemical Sciences to Global Progress: Achievements, Prospects and Challenges

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1. Introduction

This paper discusses achievements of the chemical sciences, prospects and challenges for the coming decades and some implications for future chemistry literacy.

I have written and spoken a number of times about the role of the chemical sciences in development, [4,5] including a chapter in the book on *'Chemistry's contributions to our global future'* which was produced for the International Year of Chemistry in 2011.[6] In the book's Epilogue,[7] the economist Jeffrey Sachs, who was Director of the UN Millennium Project, wrote that *"Chemistry is key to human wellbeing. The appreciation of chemistry's contributions is vital to emerging the next generation of scientists, policy makers and informed citizens."* I will try to justify both elements in this comment by Sachs: namely, the central contribution of chemistry; and the importance of thinking about the collective roles of scientists, policy makers and the public.

The chemical sciences provide not only knowledge of facts, theories and scientific processes; but also understanding of the applications of chemistry and other closely related sciences in the real world;[8] and, crucially, the field also encompasses the interfaces between chemistry and a host of other disciplines – including both scientific and non-scientific fields.

The theme of the 2015 Gordon Conference on *Chemistry Education Research & Practice* was *'Chemistry education as an agent in global progress'*, and I will start by exploring what this concept of 'global progress' might mean. 'Global progress' can be examined in terms of a number of global good things to which chemistry might be a contributor. These global 'goods' include two very important attributes of the human condition, wealth and health; but if we are seeking to extend human wealth and health we must also bear in mind that the resources of the planet are not infinite and we need to take account of the sustainability of our ways of living; we might also want to acknowledge that the benefits of advances in health and prosperity are not evenly spread among people and that achieving greater equity is also an aspect of human progress; and we might also want to factor in some of the other 'intangible' aspects of the human condition, such as peace and happiness.

There are a couple of notable points about this list: first, chemistry has connections with each of these facets of progress in the human condition; second, each of them has one or more quantitative measures available, at either the national or global level – which makes it possible to track how these indicators have changed over time and ask how chemistry and related sciences might have influenced these changes. I am going to look mainly at the first two items, but bring in examples of some of the others along the way.

First, there is one further general point I want 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"*,[9] 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 has sometimes led to severe problems of toxicity for human beings and animals; the finite resources of the world, including even the most basic chemicals like fresh water, are increasingly depleted or in short supply and this will act as a significant brake on equitable progress in the present century; chemistry has contributed weapons of war such as explosives and toxic gases; and the search for happiness and pleasure by individuals can lead them to the use of and addiction to a wide range of potentially harmful substances. 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 is 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, so that systems thinking is essential – which means that chemistry literacy must be taught in the context of real-world applications

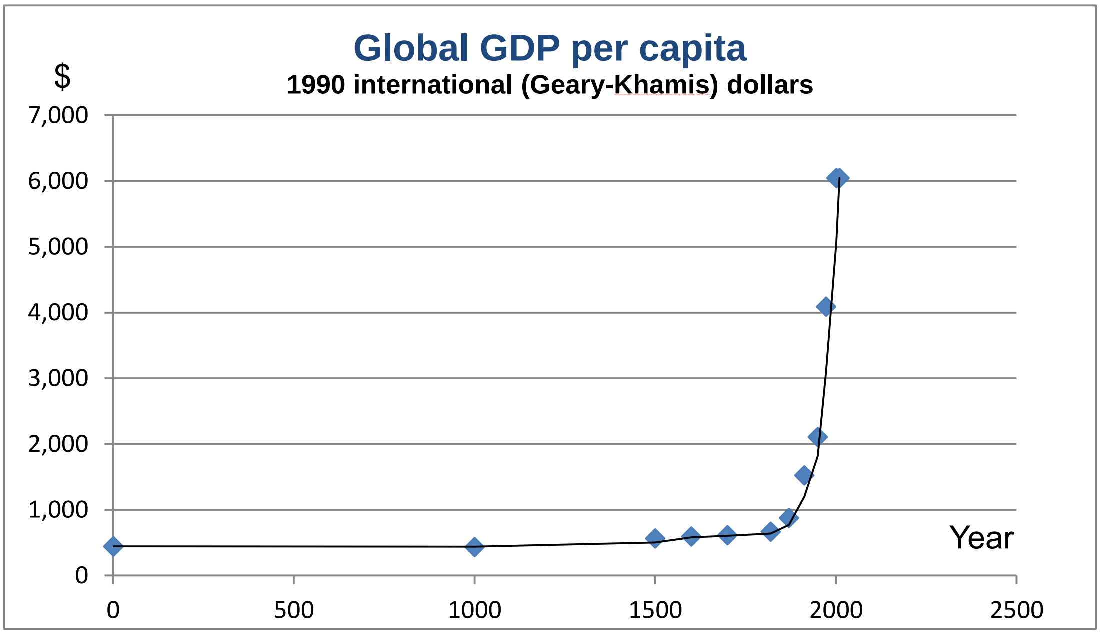
2. Achievements

Have the chemical sciences been good for wealth and health?

Wealth

The chart in Box 1 plots average global Gross Domestic Product (GDP) per capita, expressed in constant dollars, over the last 2000 years.[10] We can see that global GDP per capita remained pretty constant until just a couple of hundred years ago, but then began to rise increasingly steeply.

Box 1 Average global Gross Domestic Product (GDP) per capita (constant dollars) over the last 2000 years



Drawn from data in Ref 10

An important precursor to the steep rise in average global wealth was the Agricultural Revolution, which in Europe took place in the 17-19th centuries. 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. The chemical sciences made a major contribution to this growing global wealth:[6]

- 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 originated in work in the early 20th century on nitrogen fixation and later on the insecticidal properties of DDT, forerunners of 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.

This huge rise in global GDP per capita during the last couple of centuries has not been evenly distributed around the world. Average country incomes, as measured by GDP per capita,[11] vary by up to two orders of magnitude. It is convenient to classify countries according to whether they are high-, middle- or low-income (LMICs for low- and middle-income countries; HICs for high-income counties). This is greatly preferable to using out-of-date terminology such as 'developed' and 'developing'.

Examples of the direct role that chemistry has played in economic development at the national level include:

- Belgium is a high-income country, with a current GDP per capita of over US$45,000. A large part of Belgium's economic and industrial development since the 19th century can be traced to the chemical industry and life sciences, which currently account for around a fifth of the manufacturing sector.[12]
- Taiwan, with a current GDP per capita over US$ 20,000, 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 and in the 1990s the chemical industry was the 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.[13]

Health

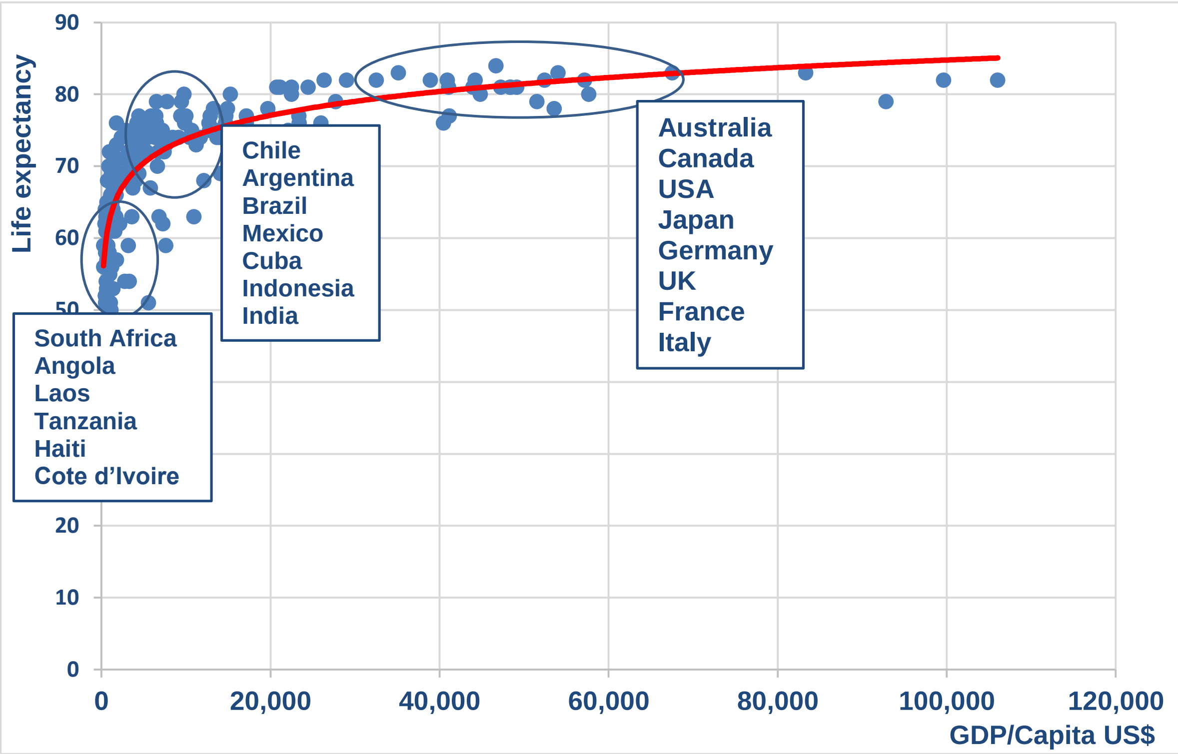
At the dawn of human history, average global life expectancy was less than 30 years – and remained below 30 years until the second half of the 19th century. It then began to increase very rapidly and more than doubled during the 20th century.[14] Over the past 150 years, average global life expectancy at birth has increased by roughly three months per year. What roles might the chemical sciences have played in this dramatic increase in average global life expectancies?

- An important underpinning development was the Agricultural Revolution, which ensured that people were better fed and not malnourished.
- The field of immunization began with the demonstration that cowpox could be used to inoculate against smallpox. Subsequently, the chemical sciences have been fundamental to the development vaccines against a wide range of deadly diseases.
- The demonstration around 1830-50 of the anaesthetic effects of certain volatile liquids and gases that had recently become available by chemical synthesis was a vastly important step for medicine, enabling advances in surgery and dentistry that were completely impractical before the development of anaesthesia.
- The era of public health dates from work by John Snow and others in the mid-19th century on contaminated public water supplies. Water purification and analysis remains one of the cornerstones of modern public health.
- The foundations of biochemistry and of our understanding of the bacterial origin of infections were laid by the work of Louis Pasteur in the 1860s.
- The foundations of medicinal chemistry were laid around 1900 with the synthesis of analgesics and antibiotics.
- The basis for metabolic medicine came from work by Casimir Funk, who isolated the first vitamin compounds and published his vitamine theory in 1912; 10 years later Frederick Banting showed that diabetes was the result of a deficiency of the hormone insulin, which he isolated and successfully used to treat diabetic patients.
- The modern antibiotic era really took off with Alexander Fleming's discovery of penicillin and introduction by Gerhard Domagk of the synthetic sulfa drugs in 1935.
- The anti-cancer era began in the 1940s with the work of Louis Goodman and Alfred Gilman on nitrogen mustard agents and anti-folate compounds.
- The transplant era was initiated in 1954 when Joseph Murray carried out the first successful human organ transplant – a transplant of a kidney between identical twins – but the real benefits could not become more generally available until the natural product cyclosporin was isolated in 1969 and its immunosuppressive properties were discovered. It first began to be used clinically in 1980 to prevent organ rejection.
- 'Science-based' drug development began in the 1960s, as a more systematic, experiment-led approach to discovering compounds with desired biological activities.
- The current era of gene-based medicine can trace its origins, among other things, to the development by the twice Nobel Prize-winning chemist Frederick Sanger and others of methods for the chemical sequencing of DNA, which enabled the inception in 1990 of the project to map the human genome.

But like average wealth, average life expectancy is not evenly distributed around the world among different countries. National average life expectancies for some countries, including Canada, now exceed 80 years, while for others national average life expectancies can be less than half that - including for some of the poorest countries such as those in parts of Africa and Central Asia.[15]

The two dramatic rises, in human wealth and human life expectancy, have run in parallel over the last couple of centuries, and it may be tempting to argue that increasing life expectancy is simply a result of economic development. However, it turns out that this is not the case, as can be shown by looking more closely at the relationship between wealth and health using a plot of average national life expectancy against GDP per capita (Preston curve).[16,17] The first thing noticeable about the Preston Curve is that it is not linear – it rises steeply for poor countries and then begins to flatten out, so that beyond a certain wealth you do not go on getting an increase in average life expectancy.[18] This is an important indicator that wealth cannot be the only factor involved. But perhaps it is just that at a certain point the natural lifespan of human beings is reached?

Box 2 Preston curve: Life expectancy vs GDP per capita 2012



Drawn from data in Refs 16 and 17

Plotting a set of Preston curves for the last century covering different time periods and in constant dollars, it is seen[19] that in any one time period there is a similar trend for the relationship between life expectancy and GDP per capita – but between each succeeding time period there is an overall increase in life expectancy. So in constant dollars, the same amount of national wealth buys more life in a later period.

Preston attributed 75% to 90% of the increase in life expectancy to improvements in health technology, while income growth was responsible for the rest. This conclusion was supported by other eminent economists – for example, Richard Easterlin concluded that the decline in 20th century mortality had its origin in *technical progress* – where the term 'technical progress', as used by economists, refers to technological advances; their diffusion and uptake in different countries; and the capacities of the countries themselves to conduct and apply research.[20] As outlines above, the chemical sciences have been very major contributors to this technical progress.

Ismail Serageldin, the Director of the Library of Alexandria in Egypt, has commented[21] that, increasingly, a nation's wealth will depend on knowledge and that the 'haves' and the 'have-nots' will be synonymous with the 'knows' and the 'know-nots'. And clearly, for the poorer countries, not acquiring and using new knowledge is not only a matter of economics – it is also a question of life and death. To put it simply – *"ignorance is fatal"*.[22]

Thus, the sciences – and in particular the chemical sciences – have been good for wealth and health, at least up to a point and for some.

3. Prospects and challenges

The world faces many very big challenges in the 21st century and there is no shortage of lists of what these challenges are:

- The third Copenhagen Consensus[23] emerged from a meeting in 2012 of a panel of experts (all economists and including 4 Nobel Prize winners) and 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"*.[24]
- Specifically in the field of chemistry: in 2009 the American Chemical Society published a major study on global challenges and how chemistry could contribute to solutions[25] and the Royal Society of Chemistry offered a roadmap for the contributions the chemical sciences can make to tomorrow's world.[26] Both reports highlighted a number of priority areas and these converge with the issues in the Copenhagen Consensus.
- In 2015, George Whitesides of Harvard University published a long essay on the need to reinvent chemistry for the 21st century and he included a list of 24 areas that he considered represent new classes of problems where the chemical sciences can make a contribution.[27] The topics in this list are extremely diverse and include the basis of life and the human mind; planetary biological and environmental systems; robotics, bionics and artificial intelligence; and energy, food, water – and even death.

Taking these and other similar lists and distilling the essentials, the planet can be seen to be facing two major sets of inter-related crises in the 21st century:

First, there is the area of health, where there are challenges due to: a growing world population that is increasingly urbanizing and ageing; the emergence of new diseases[28,29] and at the same time old diseases like TB that we thought we had conquered re-emerging 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. And then there is a second area of crisis, which relates to the fact that we are seeing the prospect of serious shortages in many key resources, including food, water, energy and materials.

And alongside these two sets of crises, two further sets of issues are cross-cutting:[30] it is a dirty world, in which pollution of land, sea and air is harming the entire biosphere; and it is a fake world, in which counterfeiting and adulteration are very widespread and, among other areas, affect food, medicine and the environment.

It must be emphasized that the nature of the challenges has three aspects: there are not just challenges for the specific science <u>content</u> needed to solve particular problems; but also for developing the <u>capacity</u> for science and in the <u>governance</u> of science – and all these aspects have implications for the kind of chemistry literacy that needs to be created.

These points are illustrated with brief examples relating to materials and drug development.

Materials

As an example, teaching about the synthesis of the alkyl halides would traditionally cover topics such as substitution and addition reactions and would consider the properties of the halogen atoms and how these affect the physical and chemical properties of the organic halides. But a broad 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. As an example, consider the case of refrigerants.

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 and sulphur dioxide were found to be too toxic and corrosive for domestic use. 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).[31] 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 being widely used as propellants in aerosol cans and in fire-fighting as well as refrigeration, as they are non-flamable.

In 1957 James Lovelock invented the electron capture detector, which is extremely sensitive for the detection of halogenated compounds in gas chromatography.[32] In the late 1960s, Lovelock was the first person to detect the widespread presence of CFCs in the atmosphere[33] 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 break down ozone.[34] It has been shown that since the 1970s there has been a steady decline in atmospheric ozone and a particularly large annual springtime decrease in stratospheric ozone over the southern polar region (this is the so-called 'ozone hole', which was discovered in the mid-1980s and has continued to grow into the 21st century). [35,36]

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, [37] concluded in 1985, was a framework agreement in which States agreed to cooperate in research and scientific assessments of the ozone problem, to exchange information, 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[38] was signed. This protocol (which came into force on 1 January 1989) 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 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[39] 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.

The negotiations for the Vienna Convention and Montreal Protocol are examples of a growing field that has become known as 'science diplomacy'. In 2010, the American Association for the Advancement of Science and the Royal Society of London held a joint meeting in London which looked at the relationship between science and diplomacy – and their report[40] concluded that this relationship has three key dimensions:

- **Diplomacy for science:** Diplomacy is a mechanism for advancing a scientific goal, particularly extensive and expensive research programmes that need to leverage the participation of multiple countries, e.g. CERN and the Human Genome Project
- **Science in diplomacy:** Science is necessary for the conduct of diplomacy or to inform issues of diplomatic concern. This includes the capacity of diplomats and diplomacy institutions to understand scientific and technical knowledge as related to bilateral and multilateral issues, e.g. cross-border public health, food safety, marine and air pollution and the work of the Organisation for the Prohibition of Chemical Weapons (OPCW)
- **Science for diplomacy (or 'science diplomacy'):** Science is a mechanism for enhancing or building bridges between countries (i.e. diplomatic purposes). Science diplomacy is especially relevant in helping develop positive engagement between countries that have strained, limited, or non-existent relationships, e.g. USA-China relations 1970s, SESAME: Israel/Middle East States synchrotron project and the biennial 'Malta conferences'.

In an Editorial in *'Science and Diplomacy'* in 2014 on the subject of 'Educating for Science Diplomacy'**.** Turekian and Wang observed[41] that the capacity to understand "science diplomacy" is necessary for foreign policy experts and practitioners, with formal and informal education and training of international relations professionals being key to increasing this capacity. But a point that I want to stress is that we need to think much more broadly than this about <u>who</u> engages in science diplomacy.

The field of diplomacy as a whole has undergone a continuous process of evolution over centuries. The old form of diplomacy predominantly tended to involve bilateral, often secret engagements between sovereign states pursuing foreign policy objectives. These engagements were usually conducted by a small number of professional diplomats and ambassadors who were carefully selected for the purpose – there is an often quoted definition[42] given by the English diplomat and politician Sir Henry Wotton: *"An ambassador is an honest gentleman sent to lie abroad for the good of his country."* But there has been a marked by a shift from this traditional form of diplomacy to more public, multilateral engagements that cover a much wider range of issues.

Science diplomacy often involves not only the traditional actors such as the diplomats, politicians and policy makers and scientific advisers; but also a host of new actors, including the media and the general public, whose influence can be brought to bear through newspapers and television and, increasingly, through the new personal and social media, as well as through their capacity to exert market forces. As Benedick[36] noted in his account of the background to the negotiations on ozone depletion: *"Millions of independent decisions by worried American consumers reduced the US market for spray cans by two-thirds by 1977, even in the absence of governmental regulation"*.

The new actors also include a host of advocacy groups of all kinds, such as NGOs, civil society associations, industry and industry-sponsored foundations and alliances.

Very often, different actors will aim to influence the outcome of diplomatic negotiations by offering their own 'scientific evidence'; or by trying to discredit the 'scientific evidence' offered by the opposing camp. And it is clear, therefore, that 'science literacy' is crucial, both to being able to participate in the dialogue and to be able to evaluate the credibility of the claims made by different factions: and everyone in society needs this capacity

Drug development and the pharmaceutical industry

Prior to the second half of the 19th century, pharmacy was a cottage industry – locally based apothecaries would each make up their own remedies and the general public was at the mercy of practices for which there was little evidence and no regulation. During the 1800s, better science and better regulation began to transform this picture. The huge demand for products that are effective and safe has driven a massive amount of investment in science, both in the public and private sectors, with the result that the pharmaceuticals and biotechnology sector currently attracts one of the largest amounts of R&D investment of any sector in the world.

So the modern pharmaceutical industry presents a very different picture to the 19th century cottage industry from which it grew. It is now a vast global industry with annual sales of over US$ 1 trillion. The USA has the largest share in this global picture, followed by Europe and Japan. But the picture is now changing, with production, consumption and research all growing in a number of the newly emerging economies. For example, China and India now rank first and second in the league of producers of bulk chemical drugs used in the formulation of medicines.

One of the challenges that the world now faces is with the levels of contaminants in environment, food and pharmaceuticals – and some of those contaminants are pharmaceuticals themselves. To take an example, a 2011 report in *Nature*[43] discussed high levels of pharmaceutical ingredients in treated effluent from wastewater-treatment plants and in effluent downstream from pharmaceutical factories, with examples coming from the European Union, India and the USA,. It is important to recognise that there has been a systemic failure, at both national and global levels, to deal with these problems. As the Nature report observes: *"The USA and Europe do <u>not</u> have regulations limiting the concentrations of pharmaceuticals released into the aquatic environment in either municipal wastewater or in effluent from manufacturing facilities."* So there is a need for better regulation – but equally importantly, a need to recognize that such regulations are meaningless without very good analytical techniques. There is a challenge to develop new analytical tools that will give reliable results that will hold up in courts of law and an overall need for pharmaceutical industry, environmental monitoring and regulatory systems to be better aligned.

A complementary area of serious concern is the contamination of pharmaceutical products themselves, and also foodstuffs, with harmful ingredients. Just to take a couple of representative examples:

- Illegal use of diethylene glycol in various pharmacy products has caused hundreds of deaths across several countries in recent years.[44] The Nigerian case in 2009 was traced to deliberate fraud by a chemical dealer in Lagos.[45,46]
- In China, widespread adulteration of infant feeding formulas with melamine (a trimer of cyanamide, added to boost the measured nitrogen content) caused serious harm on a large scale.[47,48,49]
- In the UK, an example of deliberate contamination of a pharmaceutical product occurred in 2011, when a man was prosecuted and subsequently jailed for adulterating packages of the painkiller Nurofen Plus.[50,51]

The chemical sciences can play a major role in tackling these challenges, but this requires that scientists engage in an organized way with one another and with the public, with legal systems and with policy makers for this to be effective.

There is also a massive problem of counterfeit drugs. This is a global business worth many tens of billions of dollars a year. Counterfeit medicines are estimated to constitute more than 10% of the global medicines market, with a range up to 50% in some LMICs. It remains a big challenge even in well-regulated pharmaceutical markets like that in the USA, because c. 40% of drugs in USA are imported and c. 80% of the active ingredients in US drugs come from external sources. About 10% of all counterfeit seizures made by US customs in 2014 were counterfeit medicines.[52]

These types of fraud have been made very much easier by the use of the internet as a source of pharmaceutical products and globally a high proportion of all drugs sold on the internet are counterfeit.

WHO has shown that a very wide range of drug types are involved, and a whole range of faults from little or no active ingredients to substitution with potentially harmful substances.[53] The lack of effective treatment can result in death.[54] Examples include fake treatments for malaria; it is estimated that every year hundreds of thousands of people are killed by counterfeit malaria medications;[55] and a counterfeit of the anti-cancer drug Altuzan which in 2012 was found being prescribed in the USA but had no active ingredient – a Turkish man was jailed for this in 2014.[56,57,58]

It is clear that: the problem has reached global proportions and needs a global approach; but in many places there is absence of, or weak, drug regulation. As the World Health Organization stated[59] in 1984: *"every country, regardless of its stage of development, should consider investment in an independent national drug quality control laboratory".* But: at present, of 191 WHO member states, only about a fifth have well developed drug regulation. Of remainder, about half implement some drug regulation while another 30% either have no drug regulation in place or a very limited capacity.[53] The world market for pharmaceutical anti-counterfeiting technology is estimated to be worth around US$3.4 billion in 2015.[60]

Some general conclusions are:

- There are major scientific challenges and opportunities; and the public and policy makers need to understand the problem and support the systemic solutions required. This presents challenges for developing the appropriate science literacy.
- There are challenges for regulation, giving rise to a need to develop appropriate capacities for science communication, diplomacy and literacy.

One of the biggest single challenges to global health in the 21st century is that of Antibiotic Resistant Bacteria (ARB).[61,62] In the early 20th century, before antibiotics came into use, infections caused around 43% of all deaths. Fleming's discovery of penicillin in 1928 began to change that dramatically – but Fleming was among the first to warn that development by bacteria of resistance to antibiotics was going to be a serious problem. But many antibiotics were discovered or synthesised during the 20th century and by the end of this period there was a golden age when fewer than 7% of deaths were being caused by infections.

However, during this period ARB has been growing and spreading and is now causing serious health problems and serious economic loss in every part of the world. For example, ARBs cause the majority of the 100,000 deaths a year from infections acquired in hospitals in the USA. At least 4 major factors are driving this crisis in ARB:

- Antibiotic misuse
- Massive veterinary use of antibiotics, especially to promote animal growth
- Environmental contamination
- We are also living in a period of a discovery void.

Many new antibiotics – and whole new classes of antibiotics – were discovered or synthesised during the 20th century, so that chemistry provided a steady pipeline of new drugs as the old ones gradually lost their effectiveness against the evolving strains of bacteria. But we are now in a 'discovery void', where not a single new class of antibiotics has been discovered since 1987. At least 3 major factors have contributed to this discovery void:

- **Failure in science.** Some people argue that the *"low-hanging fruit has all been picked"*; and meanwhile the promising new life science technologies have so far failed to yield new classes of antimicrobials.
- **Failure in the market system** that drives the investment in creating new medicines. Drugs for chronic diseases offer a far greater potential return on investment for pharmaceutical companies; while it has been the case for many years that any new antibiotic discovered is likely to be reserved for use as a last-resort treatment, which greatly reduces the size of the market and the profit to be made. This has been summed up as a *"systemic global market failure"*.
- Regulatory burdens. It has become increasingly difficult over time to get new drugs, including new antibiotics, registered, which acts as a further disincentive to the market in an area where the economic returns are already poor.

So the present picture, as summarised[63] in *The Lancet Infectious Diseases* journal in 2013, is that "*we are at the dawn of a post-antibiotic era"*. And as we look towards the middle of the century, we are faced with the prospect that without action, infection-related mortality may return to pre-antibiotic levels. If this happens, the whole practice of medicine will have to change and any kind of surgical procedure will carry a high risk of infection: ARBs already cause the majority of the 100,000 deaths a year from hospital-acquired infections in the USA alone.

On the science side, there is a critical need for better tools to be able to recognize resistant organisms and diagnose their type. In 2014, the UK Government launched a new Longitude Prize, worth £10 million (c. US$ 15 million) "to help solve one of the greatest issues of our time". Following a vote by the public, the challenge for the Longitude Prize is, within 5 years, to create a cheap, accurate, rapid and easy-to-use point of care test kit for bacterial infections. There is also the challenge to develop new classes of antibiotics.[64] In September 2014, the US President established a new national strategy to tackle ARB, which includes among other things, incentives for the development of new drugs.[65]

There is also need for a coordinated global effort to counter antibiotic resistance, which requires diplomacy and negotiation to get countries working together. On 25 May 2015, WHO presented a draft Global action plan on antimicrobial resistance which was agreed at the World Health Assembly. The plan has 5 major points in it and at least 2 of these, concerning awareness and understanding of the problem and optimising the use of antibiotics have implications for science literacy in the general population. Furthermore, by adopting the Global Plan, governments all committed to have in place, by May 2017, a national action plan on antimicrobial resistance that is aligned with the global action plan.[66]

What ARB illustrates very clearly is the need for systems thinking on a global scale. It is evident that human health, animal health and the environment are very closely and interactively linked together. The chemical sciences obviously have a major role to play in understanding the nature of the problem and helping to develop solutions: but that means that chemistry education must help provide the kind of literacy that gives people the capacity to see the whole system and not just one isolated aspect of the issue.

An interesting movement that has emerged in the last couple of decades is the 'One Health' initiative.[67] This seeks to integrate human and veterinary medicine and environmental science in a multi-disciplinary approach – which requires that science and policies in any one of these areas must take account of the other two.

It seems we need to have a similar orientation in our thinking about the chemical sciences, which projects them as taking a harmonized and comprehensive systems approach to understanding and solving global challenges. This kind of approach, which would incorporate ideas like 'green' chemistry, should help to ensure that the chemical sciences make their optimum contribution to the Sustainable Development Goals for the world, which the UN is currently preparing for approval in September 2015 to replace the Millennium Development Goals.

3. Conclusion

This paper has discussed challenges in science, capacity for science and governance of science; and the need to achieve a chemistry literacy that enables more effective and productive communication between scientists, the public and policy makers. In particular, there is need for:

- policy-makers to develop evidence-informed policy and understanding of the significance of research results;
- scientists and science educators to conduct policy-informed teaching and research and to develop their understanding of the significance of policy and practical constraints;
- and for both groups to develop a capacity for systems thinking.

And there is a need for the collective development of a shared, non-technical language and a shared understanding about the meaning and significance of a whole range of issues – importantly, for example, including issues concerning questions of 'certainty' and 'risk'.

Of course, none of this is at all easy – but the effort is essential if the chemical sciences are to fulfil their role in contributing to global progress in the 21st century.

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