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Chemistry 2030: A Roadmap for a New Decade

*Javier Garcia-Martinez**

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2020 has surprised us with news that only a few months ago we could not have imagined. In one way or another, we have all suffered from a pandemic that has taken far too many lives, has wiped out millions of jobs, and forced many industries to adapt in a matter of weeks to sudden changes in demand. The movement of people between countries, which is the basis of commerce and tourism, has been reduced to almost zero; and even within countries, transport has fallen dramatically, with fuel production falling to the point where, for the first time in history, the price of a barrel of oil reached negative values. All this is happening while transportation is being electrified, which is pushing the petrochemical industry to evolve from converting oil-to-fuels to transforming oil-to-chemicals. This is a monumental and complex task, especially if we consider that we must not keep increasing our production of non-recyclable plastics, solvents, and lubricants. Nobody could have imagined how the pandemic would transform the chemical sector, to the point that many chemists, most of them with no experience in virology, have re-focused their research to help with new strategies for the identification, treatment, or development of a vaccine against the SARS-CoV-2 virus. The number of publications on the subject, which surpassed 100,000 by the end of 2020,[1] is indicative of this global effort, which yielded not one, but several safe and effective vaccines against COVID-19 in less than a year.[2] Also the chemical industry has made a monumental effort to satisfy the demand of substances, materials, and personal protective equipment needed during these months.[3]

But 2020 has brought us other trends that will define this decade, such as the demand for a more just, diverse, and tolerant society. The Black Lives Matter movement has catalyzed an unprecedented reaction in favor of diversity, which, while it already existed, is now more urgent and unconditional. Chemistry, from academia to industry, is no stranger to discrimination and bigotry, and numerous initiatives have been launched in recent months demanding and providing solutions to improve the situation of women, minorities and discriminated communities. Another challenge, and perhaps the most worrying of all, is that many people distrust experts and prefer to ignore evidence. In 2020, many people marched against vaccination, some claimed that the pandemic was caused by pharmaceutical companies or foreign countries, and far too many people kept denying the clear signature of human activity on climate change or making money misleading customers by labeling their products as chemical-free. Fake news is not a new phenomenon, but technology and social media are creating a very profitable industry that lives and feeds off lies.[4] There are many lessons we can take from 2020 that will help us face this new decade.

Chemistry as the science and industry of reuse

As we start this new decade, it is useful to step back and take a broad look at what chemistry does, so we can get an idea of the magnitude and complexity of the task. Figure 1 presents the mass flow of the chemical and petrochemical sectors. Together, they extract, transform, and sell 1,388 million tonnes of fossil fuel derived-raw materials, 575.8 million tonnes of secondary reactants (excluding ores and metals), and 274 million tonnes of water per year.[5] This illustrates the scale of the chemical industry, which is expected to double its volume by 2030. According to the latest edition of the Circularity Gap Report, only about 31 % of the raw materials are transformed into useful products. The vast majority is lost as waste or emitted or dispersed into the environment.[6] In 2019, only 8.6 % of what we produced was recovered and reused, a number that decreased from 9.1 % in 2018. We cannot continue to extract, emit, and dispose at the levels we are doing now without compromising our climate, our planet and our own health. If we want to have a viable industry and a healthy planet, the circular economy cannot be just an aspiration but the key objective of chemistry. To achieve this goal, chemistry must evolve from being the science and industry of transformation (linear) to the science and industry of reuse (circular), as illustrated in Figure 2. Rethinking chemistry for a circular economy involves profound changes, from the way molecules are conceived to how processes are designed to ensure traceability, recyclability, and reuse.[7]

[*] Prof. J. Garcia-Martinez
Universidad de Alicante, Alicante (Spain)
E-mail: j.garcia@ua.es

The ORCID identification number for the author of this article can be found under https://doi.org/10.1002/anie.202014779. J.G.-M. is the Director of the Molecular Nanotechnology Lab. University of Alicante (Spain) and President-elect, International Union of Pure and Applied Chemistry (IUPAC).

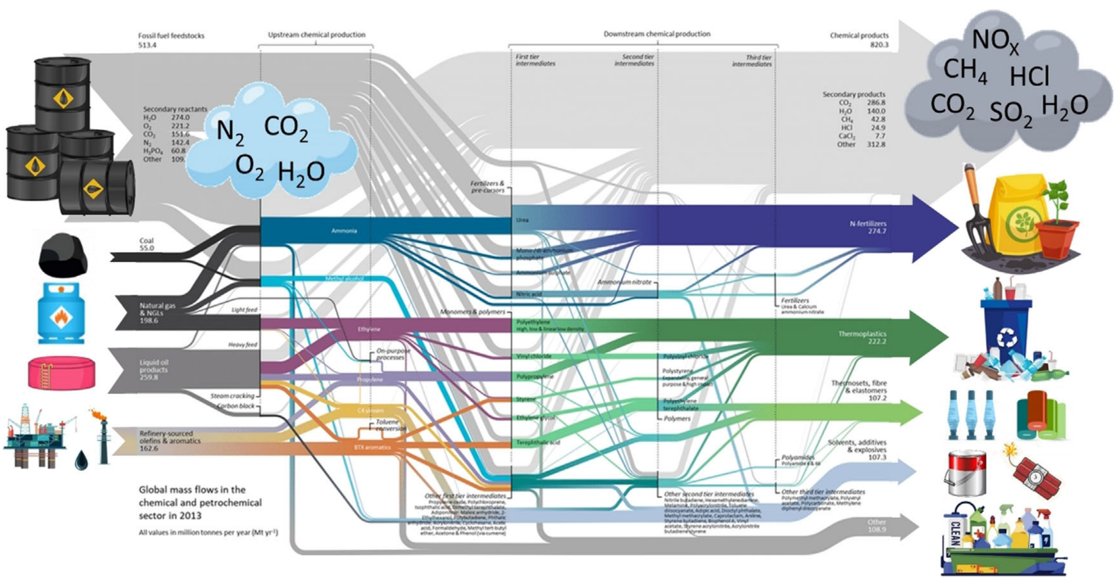

Figure 1. Sankey diagram showing the global mass flow in both the chemical and petrochemical sectors. Adapted from ref. [1].

Circularity at the molecular level means turning chemistry toward the reuse of atoms, molecules, monomers, polymers, etc—and represents an opportunity to place chemistry at the center of the new circular economy.

A good example in this direction is the enormous advances in (photo)conversion of CO_2 to produce not only solar fuels, but a great variety of platform molecules that can serve as raw materials for a new solar chemistry.[8] Exciting discoveries in materials science have led to a revolution in illumination, catalyzed by LED-based lighting technologies, energy storage, which greatly benefit from Li-ion batteries, and renewable energy, which is taking advantage of novel solutions, such as perovskite-based photovoltaic (PV) cells. These and other important advances have allowed us to more than double our economic output per unit of energy used in the last 25 years (Figure 3a). In the same period, the fraction of our electricity produced from oil sources has been cut to a third (Figure 3b) while electricity from renewable sources is growing rapidly (Figure 3c). In the same time period, the cost of direct current (DC) electricity generated by a PV module has dropped below EUR 0.03 per kWh^{-1}, that is a 250-fold price reduction in just 25 years (Figure 3d). According to Bloomberg New Energy Finance, solar PV and onshore wind are now the

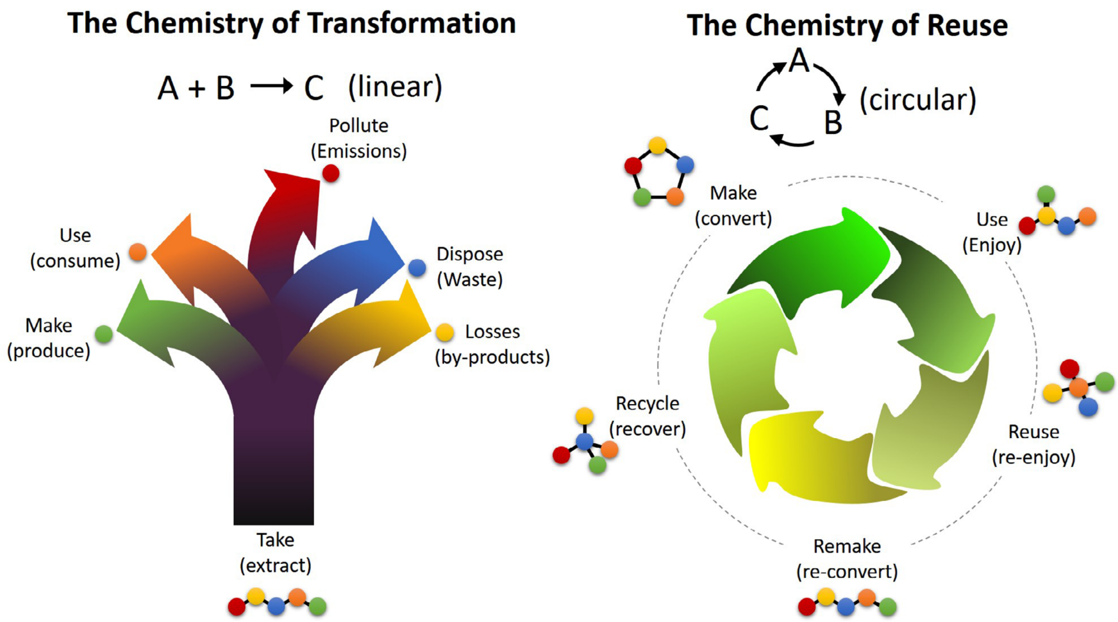

Figure 2. Schematic representation of the two models of chemistry: (left) the old linear concept based on the transformation of raw materials into products and waste and (right) the new chemistry of reuse that involves a close loop system where resources are continuously used and the production of waste is minimized.

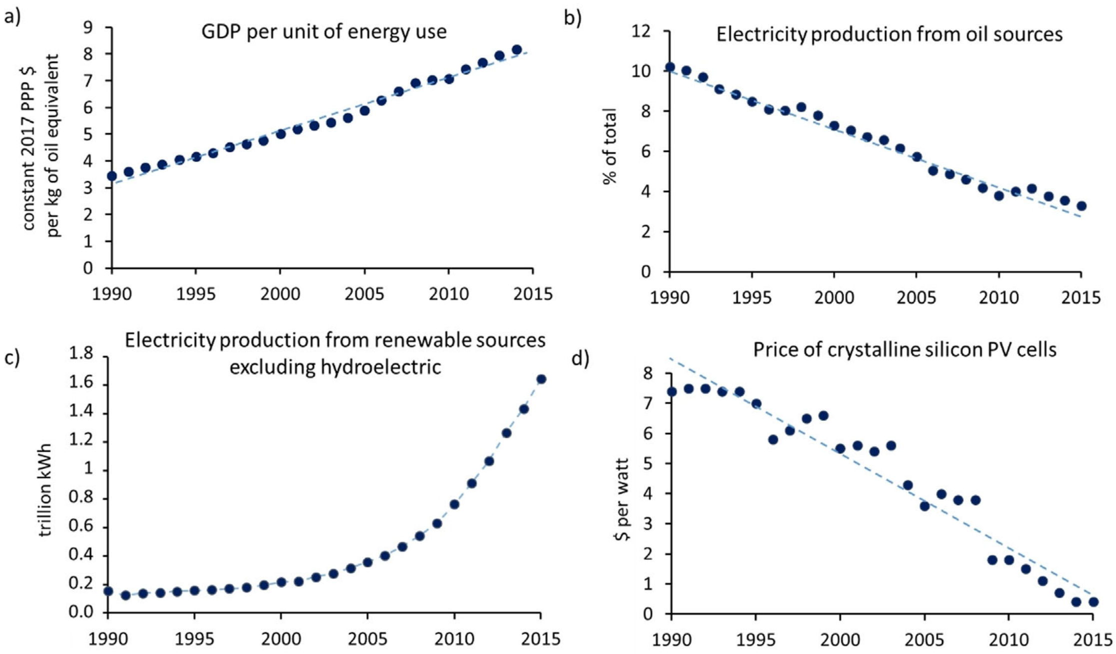

Figure 3. Evolution of some indicators that show how advances in chemistry and material science are helping in the more efficient and sustainable use of energy; a) GDP per unit of energy use; b) electricity production from oil sources; c) electricity produced from renewable resources excluding hydroelectric. Source: World Bank https://datos.bancomundial.org/; and d) price of crystalline silicon PV cell. Source: Bloomberg New Energy Finance https://about.bnef.com/new-energy-outlook.

cheapest sources of new-build power generation for at least two-thirds of the global population, and battery storage is now the cheapest new-build technology for peaking purposes in gas-importing regions, like Europe, China, and Japan. But some major challenges remain in the renewable energy field, such as its appetite for scarce elements and low recyclability of some of its key enablers, from solar panels to batteries. The biggest challenge for chemistry in the coming years is to decouple economic growth from environmental impact. To achieve this goal, chemistry must evolve from being the science and industry of transformation (linear) to the science and industry of reuse (circular), as illustrated in Figure 2.

Rethinking chemistry innovation and education

The chemical industry is going through major transformations driven by consolidation—as a result of major mergers, adaptation to increasingly demanding regulations, great volatility in prices, and increasingly complex and interconnected supply chains.[9] The need to adapt to a rapidly evolving situation has been clear in the past few months when the chemical industry had to adapt its production to suit a demand that changed in a matter of weeks. And while doing this, it has provided the disinfectants, protective materials, and drugs so much needed in the fight against COVID-19; a contribution that should not be overlooked or minimized.

Innovation, not only in products, but also in new business models and management, have proved to be the most effective way to adapt to a rapidly changing demand, regulation, and supply chains. Innovation starts by setting clear strategic goals and priorities and choosing leaders who nurture and value talent, vision, and boldness. Chemical industries have digitalized most of their processes, plants, and distributions channels, but there is an untapped opportunity to take that data and apply artificial intelligence to make full use of that information and combine it with robotics to improve safety, reproducibility, and efficiency. Similarly, and in a matter of few years, the use of machine learning and artificial intelligence in chemistry research has yielded stunning advances in a broad range of fields including catalysts, new drugs discovery, advanced materials, and, just a few months ago, a major breakthrough in protein-folding.[10]

Most chemical plants are fully digitized and machines operate many of the processes in industry, but most chemists do not know how to code an algorithm or program a robot. These new skills and the knowledge are becoming increasingly important. During the past month, many of us have had to adapt quickly to online teaching and incorporate new technologies to interact with our students, lab members, and colleagues that have been available for years, but were underused. However, the main lesson we can learn from the pandemic is not, in my opinion, about technology, but about how chemistry education can be more relevant, useful, and attractive. Systems thinking represents a great opportunity to learn chemistry in context, to incorporate key concepts like circular economy and the interconnections between chemistry and our health, our economy, and the future of our planet.[11] The most effective way to adapt chemistry research and industry to the new normal is to reimagine chemistry education. If we keep teaching chemistry like in the second industrial revolution, we will produce excellent chemists for a world that no longer exists.[12]

Building a more diverse and inclusive Chemistry

The beginning of this decade has also been characterized by a strong demand for greater diversity and inclusiveness in all facets of life. Despite the efforts that have been made, especially from the human rights movement over 50 years ago, discrimination is still a reality, and chemistry is not immune to it.

Recently, several chemistry journals have published a joint article calling for greater diversity and including some practical recommendations to improve inclusiveness, reduce harassment, and provide equal opportunity.[13] This is not just a matter of justification, there is significant evidence that these types of measures improve the quality of work and the economy.[14]

To give minorities and early-career chemists a platform and a voice, at IUPAC in collaboration with the International Younger Chemists' Network (IYCN), we have launched ChemVoices.[17] This initiative provides early-career chemists from all around the world the opportunity to discuss and collaborate on topics of common interest that are relevant to early-career chemists. ChemVoices organizes frequent webinars to provide verified information and to fight fake news and half-truths.

We shouldn't forget that 2030 is also the deadline we have given ourselves for achieving the United Nations Sustainable Development Goals (SDGs). There is no doubt that the fall in economic activity, the increase in debt, and the decrease in demand will be major obstacles for governments and businesses to invest the attention, ambition, and resources needed to achieve the SDGs. But 2020 has also offered some important lessons. Delay is costly, international cooperation is key, and scientists must engage and understand the needs of citizens. Chemistry has much to contribute to the 2030 Agenda,[15] but business as usual will not take us there, as the Global Chemicals Outlook, by the United Nations Environment Program, reminds us.[16] Driven by major megatrends, growth in chemical-intensive industry sectors such as electronics, construction, and agriculture, continue to increase, creating significant risks. But the benefits of action to minimize adverse impacts have been estimated in high tens of billions of dollars, which provides a strong economic incentive to adopt more environmentally friendly processes and strategies.

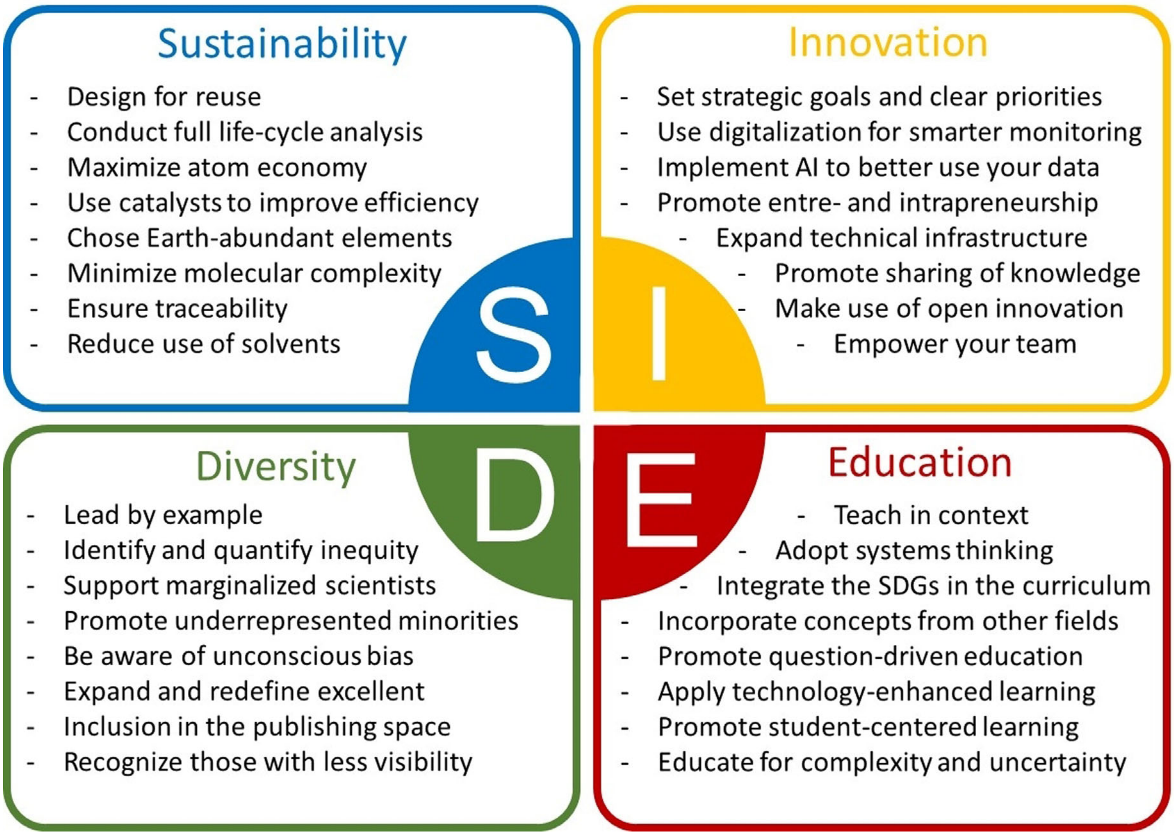

Figure 4. The SIDE vision for Chemistry 2030 comprises a number of recommendations intended to move towards a more sustainable, innovative, and inclusive chemistry. Some of them are summarized here, taken mainly from "Rethinking chemistry for a circular economy",[15] "Chemistry 4.0 Growth through innovation in a transforming world" by Deloitte,[9] "A diverse view of science to catalyze change",[13] and "Lessons from a Pandemic: Educating for Complexity, Change, Uncertainty, Vulnerability, and Resilience".[11]

This new decade poses many new challenges at many different levels. The SIDE vision for Chemistry 2030 (Figure 4) gathers key recommendations from various organizations, initiatives, and authors and provides a roadmap for the advancement of chemistry and to respond to increasingly complex and interconnected challenges.[9,11,13,15] According to those recommendations, sustainability, innovation, diversity, and education are four pillars that should define our efforts in the next decade. To get there, we need clear objectives and milestones. The SDGs are excellent, specific targets for which a broad range of indicators have been already defined to monitor progress or areas of improvement.[18] If we want to advance those pillars, chemistry organizations, from university departments to chemical companies, and from chemical societies to international organizations, should develop clear strategies with actionable priorities, indicators, and people assigned to advance their strategic plan.[19] Kenneth G. Wilson, a Physics Nobel Prize laureate from 1982 once said. "The most complex problems in science can only be resolved through the full collaboration of the entire international scientific community". In this decade, we will have plenty of opportunities to put Kenneth's advice into practice in order to build a more sustainable and inclusive future for all through chemistry.

Conflict of interest

The author declares no conflict of interest.

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Guest Editorial

Circular Economy

J. Garcia-Martinez* ________ ■■■–■■■

Chemistry 2030: A Roadmap for a New Decade

This new decade poses many new challenges at many different levels. The SIDE vision for Chemistry 2030 gathers the main recommendations from various organizations and initiatives and provides a roadmap for the advancement of chemistry and to respond to increasingly complex and interconnected challenges.