Ten Chemical Innovations That Will Change Our World

IUPAC identifies emerging technologies in Chemistry with potential to make our planet more sustainable

by Fernando Gomollón-Bel

2019 is a very special year in chemistry. 2019 marks two major anniversaries: the 100th anniversary of the founding of the International Union of Pure and Applied Chemistry (IUPAC), and the 150th anniversary of Dimitri Mendeleev's first publication on the Periodic Table of Elements [1]. IUPAC is the global organization that, among many other things, established a common language for chemistry—enabling scientific research, education, and trade. In a similar manner, Mendeleev's system classified all the elements that were known at the time, and even predicted the existence of elements that would only come to be discovered years later. These two anniversaries are closely entwined, as IUPAC has played a major role developing of the modern Periodic Table by ensuring that the most authoritative version of the table is accessible to everyone [2], establishing names and symbols for the newly discovered elements, and also constantly reviewing its accuracy through the IUPAC Commission on Isotopic Abundances and Atomic Weights.

These are two major scientific anniversaries. But we could celebrate many other things. Just over 100 years ago, Fritz Haber received his Nobel Prize [3]. This German chemist created cheap nitrogen fertilizers from nothing but air, a development that eventually detonated the huge population explosion in the 20th century. 2019 also marks the 230th anniversary of the original publication of Antoine Lavoisier's Traité Élementaire de Chimie, considered by many to be the first modern chemistry textbook. Chemistry landmarks are ubiquitous because chemistry is everywhere—chemistry is the central science connecting the physical disciplines with life and applied sciences.

Finding landmarks in the history of science is not difficult. What is really challenging is identifying the discoveries that will eventually become the big chemical breakthroughs of the 21st century. Among the thousands of chemistry papers and patents that are published every day, which will really contribute to a more sustainable future?

For that reason, while celebrating the past, IUPAC is also looking into the future with this new initiative: "The Top Ten Emerging Technologies in Chemistry" is an effort to more broadly promote the essential value of the chemical and related sciences and to identify discoveries that have the potential to change our world [4].

Experts recruited by IUPAC selected the "Top Ten Emerging Technologies in Chemistry" highlighted in this article from a pool of nominations submitted by chemists from around the globe. The following are emerging advances in the chemical sciences that hover between the embryonic 'eureka' moment at the lab and industrial application. Most certainly, in the near future, we will look back at these selections of innovative technologies and celebrate how they changed the world in which we live.

Nanopesticides

World population keeps growing. Some predictions suggest we will be almost 10 billion humans by 2050. Feeding that many people will require a huge increase in agricultural production, while keeping crops sustainable: minimizing the environmental impact in terms of land use, reducing the amount of water needed, and mitigating the contamination by agrochemicals such as fertilizers or pesticides. Unsurprisingly, nanotechnology is attracting quite a lot of attention beyond the pharma and health industries. Tailored nano-delivery systems could also become a great tool for farmers, as it would eventually allow them to tackle the main problems of conventional pesticides such as environmental contamination, bioaccumulation, and the huge increase in pest resistance. There are very few publications that carefully analyze the benefits—and risks—of so-called "nano-agrochemicals" against their conventional alternatives [5]. In most cases, the increase in efficacy is quite limited. However, in some cases researchers have observed

improvements by an order of magnitude under laboratory conditions. We still need a proper assessment of the efficacy of nanopesticides under field conditions. That is why some companies still investigate their potential, proving that there is still hope for this technology [6]. Canadian Vive Crop is possibly the best example, selling products that have demonstrated better absorption and less environmental impact than their non-nano commercial alternatives. Moreover, this company recently received the approval of the U.S. Environmental Protection Agency to commercialize various nano-encapsulated insecticides and fungicides. Nanotechnology may not be the only ingredient to a successful new, more sustainable agriculture, but it will certainly lead to more sophisticated agrochemicals with a lower impact on the environment and human health.

Enantio-selective organocatalysis

Chemists have always been inspired by nature. A few years back, researchers dreamt of a new kind of catalysts that, like most natural enzymes, would not require the use of expensive metals. “Organocatalysis” was born in the late 1990s and it has not stopped growing ever since. According to Paolo Melchiorre, one of the leading experts in the field, organocatalysis was successful because “[It] was quite democratic, everyone could have access to it without needing expensive reagents or a glovebox, which allowed many young researchers to start their independent careers, and quickly assembled a community of international experts that become a great incubator of ideas for catalysis without metals,” he explains.

Initially, some chemists criticized organocatalysis for not being as green as it claimed to be—it needed high catalyst loads and, moreover, it was hard to recover the catalyst after the reaction, which seem to go against the very definition of catalysis. However, Melchiorre points out how researchers have overcome most of these problems. He says that the original focus of organocatalysis was “to develop new methods rather than decreasing the catalyst loads.”

Nevertheless, because chemists understood the industrial implications that lowering the catalyst amount could have, they crafted ways of creating chiral carbon–carbon bonds using just part per millions of organocatalysts. “This is still not comparable to metals, but the cost is significantly cheaper,” he adds.

Chemists have also developed solutions to better recover the catalysts—Ben List immobilizes them on solid substrates like nylon [7], which is just one of the many possible answers. Melchiorre highlights how organocatalysis has seeded the chemical landscape and eventually sprung other fields, especially photoredox catalysis, which allows new types of transformations: “[David] MacMillan created the link between the two fields. Light activation enabled reactions such as the alkylation of aldehydes with enamines, which couldn’t be done with classic organocatalytic methods.” Many other fields have emerged from organocatalysis, and now industries have scaled-up asymmetric organocatalytic protocols to synthesise fine chemicals and drugs.

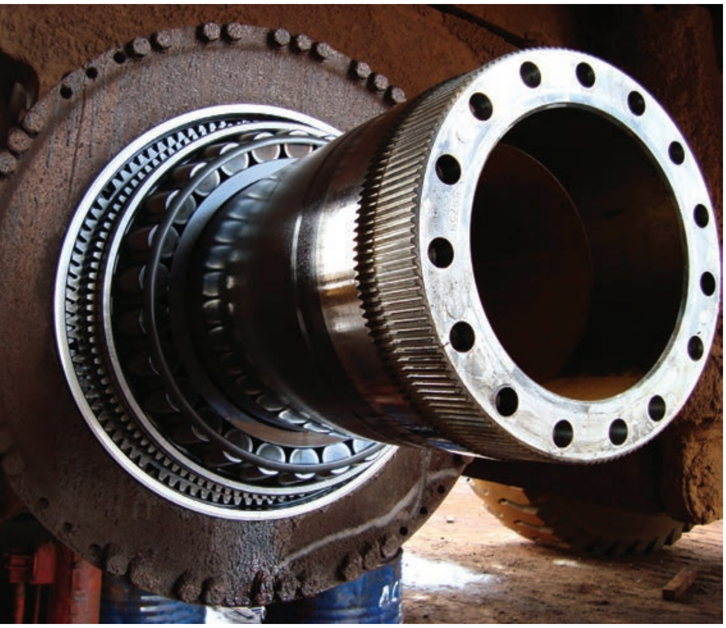
Solid-state batteries

Solid-state batteries were already envisioned in the 19th century by pioneer chemist Michael Faraday. However, their development never become a reality until quite recently. Now, important industries from a variety of sectors such as Bosch, Dyson, Toyota, and Intel are investing billions of dollars in this technology. John Goodenough, co-inventor of the now omnipresent lithium-ion batteries, recently unveiled a battery that uses glass as the electrolyte—proving that solid-state batteries are closer to market than ever. Compared to lithium-ion batteries that power our smartphones, tablets, and laptops, solid-state batteries are lighter, allow higher energy storage, and perform well at high temperatures. Moreover, unlike the electrolytes used in lithium-ion technology, solid-state electrolytes are not flammable, which could potentially avoid spontaneous fires and explosions, like the flames that darkened the launch of Samsung Galaxy Note 7 a few years back. However, the new technology is still very expensive.

As for many other applications, polymers may be the best and most economical solution. French transportation company Bolloré is already fabricating and commercializing polymer-based solid-state batteries, which they use mostly for network connected sensors.

According to polymer expert Tanja Junkers, “charge transporting polymers [are] truly fascinating—we have just yet seen the very beginning of what will be possible in [the] future.” There is still a lot of research to be done, especially because solid-state battery components are so closely bound together that it is quite complicated to understand how each of them behaves.

Academics and industrial researchers are closely working together to develop better non-destructive, operando technologies—electron microscopy and nuclear magnetic resonance—to understand how solid-state batteries perform. For most uses, the technology will still need a few more years of development [8].



Flow chemistry

Chemistry is key in achieving some of the United Nation's Sustainable Development Goals (SDGs), a blueprint to attain a better and more sustainable future for all by the year 2030. Among them, flow chemistry, where reactions are run in a continuously flowing stream rather than in batch, is particularly critical for tackling SDG12: responsible consumption and production. Flow chemistry processes eventually minimize the risk of handling hazardous substances and increase productivity, both preventing harm and lowering the environmental impact. Although some people consider flow chemistry to be on a very early, small-scale laboratory stage, efficient industrial applications are increasingly common.

Back in 2015, chemists at MIT demonstrated the potential of flow chemistry to create tailored polymers that would be unattainable by classical batch techniques. According to the experts in the field, the flow process is quicker and simpler, yet more reliable, which is quite in line with the SDG goals.

More recent examples have even shown the potential of flow chemistry to withstand hazardous reagents such as organolithium compounds. Merck chemists achieved a 100kg-scale synthesis of a precursor for verubecestat, a phase III candidate to treat Alzheimer's disease. Other recent examples include the flow synthesis of ciprofloxacin, an essential antibiotic, and an automated flow system developed by Pfizer capable of analyzing up to 1500 reaction conditions a day, speeding up the discovery of optimal synthetic routes for both new and existing drugs.

Reactive extrusion

Along with flow chemistry comes reactive extrusion, a technique that allows chemical reactions to happen completely solvent-free. The elimination of potentially toxic solvents makes this process environmentally friendly. It creates however many engineering challenges as it would require a complete redesign of the industrial processes that are now in place. Although extrusion processes have been widely-used and investigated by polymer and material experts, it is only now that other chemists are starting to dig into their possibilities in the preparation of organic compounds. Classic extrusion methods involve grinding reagents in a ball mill, but more advanced extrusion technologies using screws could even allow these solvent-free reactions to operate in flow setups. Once again, the downside lays on effectively adapting the systems and scaling them up. In their labs, chemists have used ball mills to prepare several attractive products—amino acids, hydrazones, nitrones, and peptides—and have achieved some very classic organic reactions—Suzuki coupling, click chemistry—but the examples in reactive extrusion conditions beyond polymers remain quite elusive [9]. However, the scarce exceptions show great promise [10]. Biotech company Amgen reported the optimized synthesis of co-crystals with potential use in the treatment of chronic pain, which was also the first example of mechanochemical synthesis scaled-up to several hundred grams. Furthermore, scientists in the UK have used reactive extrusion to efficiently prepare deep eutectic solvents [11]—a class of ionic liquids that could become the new generation of green, non-flammable solvents. Both previous examples involve the formation of intramolecular interactions, but not the creation of new covalent bonds. However, chemists have recently reported the formation of metal organic frameworks (MOFs) [12] and discrete metal complexes by screw extrusion, opening the door to new possibilities towards a cleaner and more sustainable solvent-free chemistry.

MOFs and porous materials for water harvesting

According to the United Nations (UN), water scarcity affects more than 40 % of the global population and is projected to rise. On top of that, three in ten people lack access to safely-managed drinking water services. Chemistry could bring a solution to this problem identified as SDG 6 [13] "to change our world" using porous materials, particularly metal organic frameworks (MOFs). Porous materials like MOFs have a sponge-like chemical structure with microscopic spaces that can selectively trap molecules, from gases—hydrogen, methane, carbon dioxide, water—to more complex substances, such as drugs and enzymes. While some researchers were focusing on the uses of MOFs in drug delivery and gas purification, Omar Yaghi accidentally discovered their great potential in capturing water from the atmosphere. “When we were studying the trapping of post-combustion gases uptake into MOFs, we noticed that some MOFs exhibited a unique interaction with water molecules,” explains Yaghi. Then, they wondered whether the same material “[could] be used to trap water from the atmosphere in arid climates, and then be released easily for collection.” This technology is unique, because “it can harvest drinkable amounts of pure water from the dry desert air with no energy required other than the natural sunlight,” says Yaghi. Just one kilogram of MOF could harvest 2.8 litres of water a day at a humidity level as low as 20 %. While working on higher capacity, potentially cheaper versions of the water-harvesting materials, Yaghi is “already partnering with companies to test their MOF water harvesters on an industrial scale.” There are other porous materials with similar abilities such as silica-based and inorganic porous solids, and the recently-reported biomimetic porous surfaces that mimic the structure of cactus spines [14]. Most of them, Yaghi argues, are not as productive as MOFs in taking up water from low humidity air. Nevertheless, further research may of course explore all possibilities to find the best solution, not only for harvesting water, but also for purifying it, guaranteeing the achievement of one of the most important UN goals—achieving access to adequate and equitable sanitation and hygiene for all.

Directed evolution of selective enzymes

Directed evolution of enzymes received the 2018 Nobel Prize in Chemistry. Enzymes produced through directed evolution are used to manufacture everything from biofuels to pharmaceuticals. According to the Nobel committee, chemists such as 2018 Laureate Frances H. Arnold “have taken control of evolution and used it for purposes that bring the greatest benefit to humankind.”

“Directed evolution requires the experimental testing of tens of thousands of variants, but [at the end] provides highly active enzymes,” explains Sílvia Osuna, who investigates enzymes through advanced computational methods. She believes that the most active enzymes created through rational design “still perform quite poorly in comparison with the natural enzymes and enzymes artificially evolved in the lab.” According to Osuna, the most interesting fact about directed evolution is how “mutations [that are] remote from the enzyme active site have a tremendous effect on the enzyme catalytic activity.”

It is only through analyzing artificially evolved enzymes that we have come to learn this. Her field, studying enzymes through computation, could be the key to identifying similar trends, thus better understand directed evolution. “Computation is one of the many tools, together with protein engineering advances, gene synthesis, sequence analysis, and bioinformatics, that will help us chemists make more focused [enzyme] libraries,” she concludes.

The limits of directed evolution are yet to be discovered. In her most recent paper [15], Arnold “hacked” plant enzyme cytochrome P450 using directed evolution. Now, they can easily catalyze the transformation carbon–hydrogen bonds into the more complicated asymmetric carbon–carbon bonds.

From plastics to monomers

“Circular economy is certainly the goal,” says Tanja Junkers. Once again, chemists should be inspired by nature. There, “everything is reused, and we should do the same with our synthetic materials.” This strategy will kill two birds with one stone, “it will solve the problem of recyclability in the long term, and the [need of] finding suitable sources for the main [polymer] building blocks.”

Some polymers, like polylactic acid (PLA), can be easily recycled into their monomers just by using heat.

Others, such as polyethylene-terephthalate (PET), can be similarly broken down into their most basic units. First, the polymer is treated with ethylene glycol, which breaks the long polymer chains down into oligomers. These smaller fragments melt at lower temperatures and therefore can be filtered to remove any impurities. Then, once the material has been purified, it's completely broken down into the monomers, which are then purified again by distillation.

Beyond classic chemistry, and much like Arnold's approach to enzymatic transformations noted earlier, some bacteria have evolved such that they can also break down PET into pieces. Sometimes plastic is the only source of carbon around and you need to adapt if you want to survive. At least one species of *Nocardia* possesses an esterase that can break the ester bonds in PET [16] and, more recently, Japanese researchers discovered *Ideonella sakaiensis*, a bacterium that can disintegrate a PET plastic film in about six weeks thanks to two different enzymes [17]. Yet, recycling is expensive, and "the world of plastics works on so small margins that every cent matters," says Junkers. Chemists are looking into cheaper options towards a circular economy. Moreover, the price of plastic will slowly rise as oil becomes less abundant. But, beyond that, we have to raise awareness that cleaner plastic may be more expensive, but worth it. "Society must be willing to pay a [higher] price for more sustainable options," concludes Junkers.

Reversible-deactivation of radical polymerization

"Reversible-deactivation of radical polymerizations (RDRP) was invented more than twenty years ago and revolutionized the world of polymers," explains Junkers. "These methods all rely on mechanisms that impose control over otherwise almost uncontrollable chain reactions, allowing us to design polymers with an accuracy that comes close to what nature is doing," she says. RDRP polymers have found uses in a myriad of sectors: construction, printing, energy, automotive, aerospace, and biomedical devices are just some examples. "Most of the time, we are using these polymers without realizing it," says Junkers. RDRP has become a very powerful and useful tool for industrial chemists.

But there is still plenty of room for further innovation, especially towards finding more environmentally-friendly polymerization solutions. There are now many methods to control RDRP processes using only light, even without the need of using metals [18]. In recent years, chemists have also developed RDRP methods that work in flow systems, which will allow them to move towards greener synthesis of polymers and plastics [19].

Finally, chemists have also mastered polymerization processes that work in aqueous media, avoiding the use of volatile or hazardous solvents. The most recent advances allow them to obtain ultra-high-molecular-weight polymers in water in just a few minutes [20], while keeping an exquisite control of the polymer branching. Some of these processes can work with a very low-energy light source, even just sunlight in some cases. Despite being a well-established technique, we can be certain that RDRP methods will continue to innovate, yielding an even broader commercial success [21].

3D-bioprinting

Bioprinting is one of today's most promising technologies. Using 3D printers and inks made out of living cells and also biomaterials and growth factors, chemists and biologists have managed to fabricate artificial tissues and organs almost indistinguishable from their natural versions. 3D-bioprinting could revolutionize both diagnostics and treatments, as artificial tissues and organs could be easily used for drug screening and toxicology research. This technology could even lead to the creation of tissues and organs for ideal transplants that would not require a donor. Currently, scientists can already 3D-print tubular tissues (heart, urethra, blood vessels), viscous organs (pancreas) and solid systems (bones) [22]. Recently, Cambridge researchers even managed to 3D-print a retina, carefully depositing layers of different types of living cells to generate a construct that architecturally resembles the native eye tissue [23].

Chemistry plays a central role in all the steps of this very complex process. First, organs and tissues need to be "scanned" in order to have a computational model. This is done using imaging techniques like computerized tomography (CT) scans and magnetic resonance imaging (MRI), both of which usually require chemical contrast agents such as gadolinium dyes. Then, bioprinting itself requires a myriad of chemicals to stabilize the bio-inks, trigger the assembly of the cells, or act as a scaffold for the printed tissue.

And finally, the 3D-bioprinted object needs to maintain its structure and form over time, a process for which both physical and chemical stimuli are required. Moreover, much like in any transplant or surgery, there is always the risk of the body rejecting the printed tissues. Understanding the chemistry of cell-cell recognition, mostly ruled by sugars that coat the membrane in the form of glycolipids and glycoproteins, is key to minimize rejection. Chemistry, in the center of all the crossing disciplines behind the highly-complex 3D-bioprinting, will be key in the further development of this fringe technique that, according to some experts, could even build new organs that are better than the existing biological ones [24].

With the "Top Ten Emerging Technologies in Chemistry" initiative, IUPAC not only celebrates its last 100 years, but also glances into the future of Chemistry. Each of these advances holds an enormous potential to ensure the well-being of our society and the sustainability of our planet Earth. Thus, IUPAC will continue to showcase these emerging technologies in chemistry, materials, and engineering in future editions of *Chemistry International*. The goal is to promote and highlight the ubiquitous contributions of Chemistry in our daily lives, and to inspire the new generation of young scientists to fearlessly embrace the challenges we face, empowering them to find solutions through research, entrepreneurship, and creativity.

Chemistry innovation will drive the change towards achieving the Sustainable Developments Goals and, ultimately, to accomplish the mission of IUPAC—to apply and communicate chemical knowledge for the greatest benefit of humankind and the world.

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