

IUPAC's 2025 Top Ten Emerging Technologies in Chemistry

by Fernando Gomollón-Bel

Since 2019, the International Union of Pure and Applied Chemistry (IUPAC) has identified the Top Ten Emerging Technologies in Chemistry [1]. This initiative showcases the strategic and innovative contributions of chemistry and chemists to the sustainability and the well-being of society, [2] serving as a platform to promote up-and-coming breakthroughs to catalyse commercial uptake and technology transfer [3]. This year's selection, as usual curated by a team of experts from a pool of proposals submitted by researchers worldwide, includes technologies capable of tackling the climate crisis, transitioning to a sustainable supply chain, and providing promising solutions for better healthcare. Read on to discover the 2025 top ten technologies in chemistry with a transformational potential.

Xolography

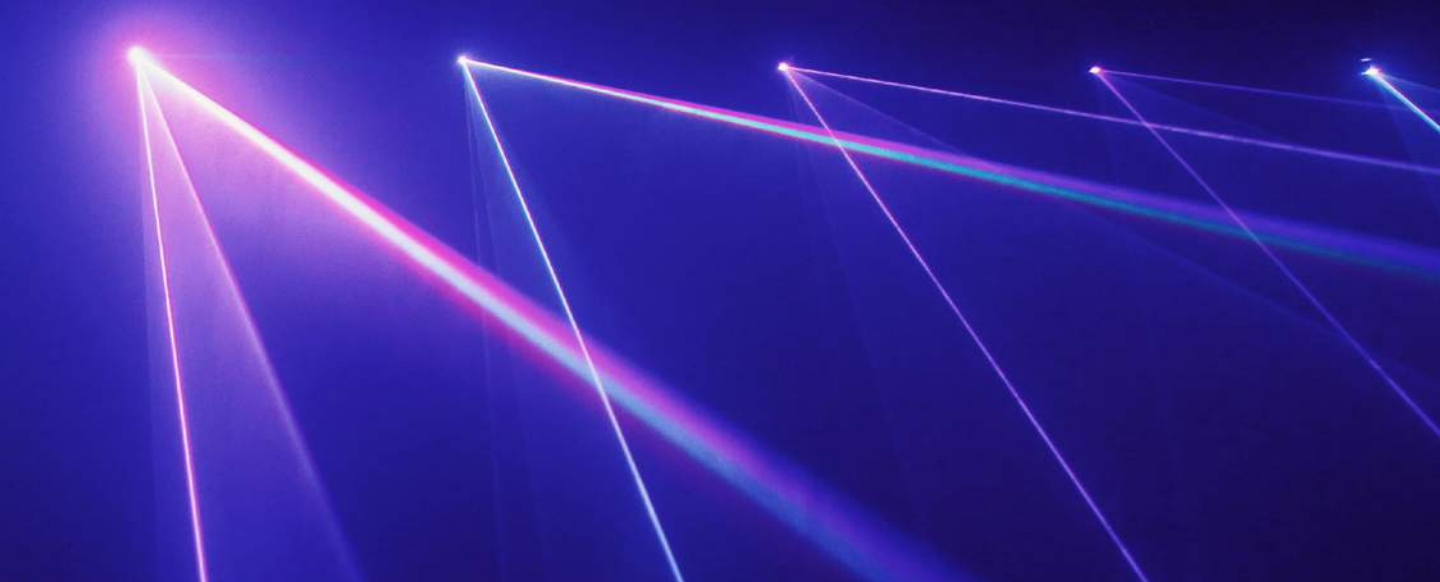
The potential of 3D printing was already highlighted early in the IUPAC Top Ten [1]. Plus, polymers and advances in this broad field often make it into the selection, given the tremendous importance of making manufacturing more substantiable, easier to recycle, and safer by design [4]. In this sense, xolography represents an interesting step forward in innovation and, particularly, in 3D printing. This technique could revolutionise the production of plastics by creating structures with the precision of printing, but without the hassle and time requirements of traditional alternatives, which involve a layer-by-layer approach. First introduced only a few years ago in 2020, [5] xolography combines photochemistry and materials science to print polymers with precision and an unparalleled level of detail. The secret lays in simultaneously using two different wavelengths—one to activate sections of a resin responsive to UV light, and another to quickly cure the activated regions, ensuring the solidification of the structure. Overall, xolography allows the generation and creation

of 3D printed polymers, even complex hollow structures and intricate moving parts, very efficiently and without any extra support scaffolds [6]. Overall, this solution overcomes most of the limitations of the traditional 3D printing of polymers, particularly in the production of interconnected pieces. Beyond precision, xolography offers an impressive speed [7]. Some studies suggest xolography is several orders of magnitude quicker than classic technologies, making structures in just a few seconds that would take layer-by-layer printers more than thirty minutes [8]. Moreover, the most recent advances in the field allow for continuous printing processes [9] and even efficient results under micro-gravity [10]. One of the pioneers of the technology is the co-founded start-up, Xolo, based in Germany, which raised a Series A funding round of eight million euros and applied for several patents, proving the potential of xolography in the manufacturing market [11].

Carbon dots

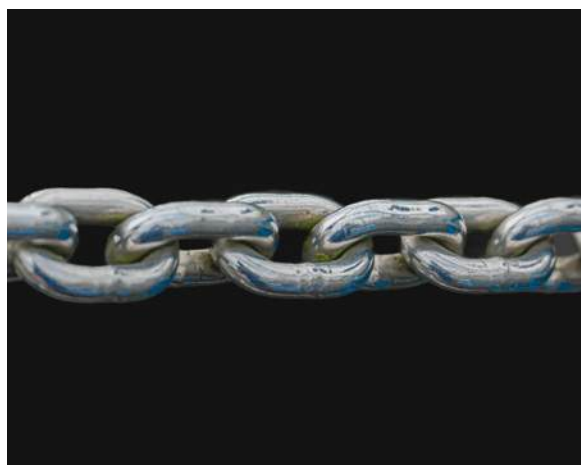
In 2023, the development of quantum dots—colourful, ubiquitous particles used in applications from LEDs to the treatment of tumours—won the Nobel Prize in Chemistry [12]. Carbon dots represent a greener alternative, usually also more biocompatible. Their advantages arise mostly from the possibilities in personalisation, thanks to simple strategies to functionalise





and decorate these carbon structures to convey applications in sensing, bioimaging, drug delivery, catalysis, solar cells and energy storage, among others [13]. The structure of carbon dots varies, depending on the preparation process. Some feature a crystalline core, such as a few layers of graphene fragments (*i.e.* carbon *quantum* dots), while others count on a core of amorphous graphite (*i.e.* carbon *nano* dots) or carbonised pieces of polymer (*i.e.* carbon *polymer* dots). Overall, whatever synthetic strategy is used, the value of carbon dots lies in sustainability, stability, solubility and, most importantly, low toxicity [14]. The latter, together with tuneability, makes carbon dots an attractive alternative for applications in biology and medicine. Thanks to strategic structural modifications, chemists are able to tune and tailor the fluorescence of carbon dots for easy identification, as well as modify them with linkers and tags to direct them to specific structures in biological systems, such as antibodies, organelles, and cells [15]. This is extremely useful in sensing and imaging for the detection of diseases and defects in biological tissue, for example, but is also useful for treatment. Carbon nano-dots could carry cargos for drug delivery and potentially provide solutions for therapeutic applications, including phototherapy and chemotherapy [16]. Recently, carbon dots derived from citric acid showed promise in the treatment of base burns, reducing the recovery period. Perhaps more interestingly, the processes for producing carbon dots often rely on sustainable syntheses and inexpensive, abundant resources such as biomass, in line with the principles of green chemistry. Last, but not least, the possibilities of personalisation have led to the discovery of chiral carbon dots, which open new avenues in the sensing of structures, including drugs, DNA, amino acids, sugars, and other biomolecules and bioactive compounds. Moreover, chiral carbon dots present unique opportunities in catalysis, including photocatalysis, electrocatalysis, click chemistry, and even as an alternative for the site-selective cleavage reactions of CRISPR gene editing [17]. Although still

mostly in the realm of research, carbon dots could make it to the market soon, partly thanks to several start-ups and spin-offs around the world. An interesting example is Qarbotech in Malaysia, a company that created a carbon dot solution to boost the efficiency of photosynthesis, pioneering applications in agriculture.



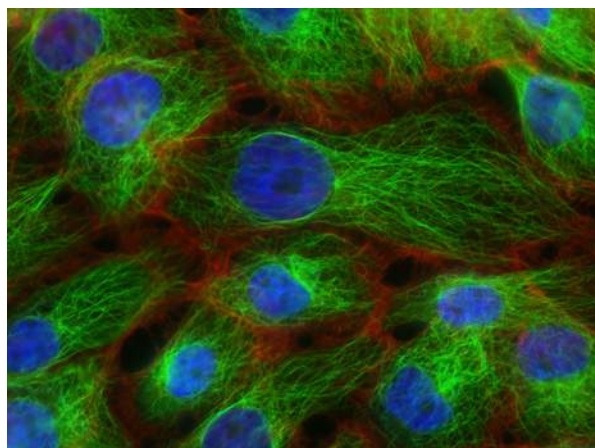
Nanochain biosensors

Nanotechnology has been present in the Top Ten selections since the initiative was created, representing an estimated ten percent of the technologies. In this same spirit, nanochains could provide a promising solution for biosensing. Since the start of the current century, the modification of one-dimensional nanostructures has been explored as a strategy to selectively and sensitively detect molecules, particularly small molecules and biomolecules, with a combination of electrical, electrochemical, optical and mechanical methods. The recipes rely on a variety of products, including gold nanoparticles, carbon nanotubes, and silicon nanowires, among others. Decorated with different “detectors,” such as enzymes, antibodies, proteins and DNA fragments, these nanosensors reached limits below pico- and femtomolar concentrations, in some situations spotted

even a few single molecules [18]. This surpasses the limits of most microscopy techniques and opens the door to innovative solutions—among them nanochains. Nanochains were inspired originally by research in magnetic nanoparticles, which very easily assemble into sequenced, stable structures, also identified and isolated in some living organisms. Today, researchers prepare nanochains on-demand, decorated with a variety of fragments for applications in catalysis, imaging, and drug delivery [19]. The versatility of nanochains allows not only for different uses, depending on the surface modifications, but also sparks solutions in microfluidics and “lab-on-a-chip” devices, where the nanostructures serve as a strategy for separating and selecting substances, as well as serving as a solution for mixing the reagents—if applied as a nanoscale stirring rod. Imagine minuscule magnetic filaments, made of smaller particles, all coated in reactive probes, such as antibodies [20]. Additionally, another virtue of nanochains lays in an ability to amplify scattering signals, expanding the limits of detection of optical microscopes from two hundred down to fifty nanometres, which allows the direct observation of viruses. This inspired researchers to create more sensitive tests for pathogens such as SARS-CoV-2, H1N1, and H3N2, which cause diseases like COVID and the flu. In this case, the nanochains consist of carefully synthesised non-metallic nanoparticles, modified with the relevant biomarkers ready to detect the different diseases [21]. Other studies present nanochain biosensors for heart diseases, kidney infections, migraines, and some examples of tumours. Some nanochains are easily dispersed in solutions, which facilitates the fabrication of printed biosensors, almost “à la carte.” It may still seem a bit early for commercial applications, but nanochain sensors have found a niche in personalised point-of-care tests and could soon start a revolution in treatments after some success in therapies for hard-to-treat cancers [22].

Synthetic cells

Everything is chemistry—including our own cells. And, for years using different approaches, chemists and biochemists have tried to recreate our own cells in the lab [23]. On the one hand, our synthetic cells could serve as “simulations” or simplified models to study and understand processes such as gene expression, metabolism or molecular communication in biology. On the other hand, our synthetic cells could provide pioneering applications in biotechnology and medicine, for use in research, diagnostics and therapeutics, with totally-tailored properties, including examples such as the synthesis and selective release of drugs [24],



or even technologies for the capture and utilisation of carbon dioxide [25]. Generally, the creation of such synthetic cells is classified as either “top-down” or “bottom-up.” The former implies the simplification of an existing living structure, removing any parts strictly non-essential to tailor the cell’s composition. This is the idea followed by a team in the J. Craig Venter Institute in the US, credited with the creation of the “first minimal synthetic cell,” reducing the original genome of a specific bacteria to half its usual length, while still staying viable as an organism [26]. These synthetic structures can shed light into the secrets of life, as well as provide a platform for personalised gene expression, which could create “cell factories.” Similar to genetically-engineered bacteria, these structures could enhance the efficient production of chemicals, biofuels and drugs [27]. “Bottom-up” methods make a cell from scratch, usually using lipid vesicles to encapsulate other biomolecules, including nucleic acids, proteins, enzymes, and even simplified versions of organelles. This approach simplifies the issues related to genetic engineering and expression, and makes the creation of cells simpler, faster, and ready for large scale development. The applications of artificial cells range from drug synthesis and delivery to bioreactors and biological “computers.” [28] Indeed, the current complexity expands from expressing genes, with examples that change shape, move around, and communicate [29]. Although still in early stages, researchers stay positive about the potential of synthetic cells. Some specialists even consider applications such as the mRNA COVID-19 vaccines, as well as other drug formulations using liposomal encapsulation, as a simple example of “bottom-up” structures, resembling synthetic cells, demonstrating the possibilities of this technology. Overall, synthetic cells could provide a better understanding of life and, simultaneously, solutions to boost our health.

Single atom catalysis

Heterogeneous catalysts have continuously dominated the market. Traditionally, metals make the active sites, dispersed on supporting structures such as activated carbon and ceramic materials. However, at the beginning of the current century, chemists envisioned an exciting idea for more efficient and sustainable catalysis in industry, which could combine the capabilities of heterogeneous catalysis with the precision and selectivity of enzymes—single atom catalysis (SAC) [30]. Instead of supporting clusters of catalyst atoms or nanoparticles, SAC uses isolated, single atoms, attached to a supporting surface. Therefore, every catalytic site stays exposed to the reagents, which consequently conveys a theoretical atom efficiency of 100%, maximising reactivity and, perhaps most importantly, sustainability. This is due not only to the higher efficiency, but also to the reduction in required amounts of metal and increased recyclability—SACs have demonstrated a sustained state of activity after several recovery and recycling reactions [31]. In the past two decades, researchers have reported results with SACs across the periodic table, including not only with the more traditional platinum, palladium, and rhodium, but also with the more abundant alternatives such as iron, nickel, and copper [32]. The latest, for example, has emerged as an exciting catalyst for the electrochemical conversion of carbon dioxide into value-added products [33]. Additionally, SACs sometime showcase interesting and unique catalytic activity, different from bulk heterogeneous options. The different coordination environments which, in turn, also prompt tuneability and modifications, create a special electronic structure in the active sites, affecting selectivity and stopping undesired reactions. The reactivity of SACs has been reported as “unique and multi-faceted.” [34] This has

become increasingly attractive for researchers working in energy solutions such as CO₂ valorisation into chemical fuels, water splitting, and the synthesis of green ammonia [35]. SACs have also successfully catalysed commercial reactions, such as Suzuki couplings [36], and now progressively advance towards more scalable, resilient solutions, ready for the mass market. Catalyst companies such as Johnson Matthey are reportedly working on sustainable solutions using single atom catalysts, and commercial suppliers often offer preparations with SACs for reactions in energy conversion, petrol refining, and advanced synthesis. Now, the most likely next frontier is chiral catalysis. Some studies have explored the possibilities to perfect the “final frontier” of catalysis even further, replicating the selectivity and specificity of enzymes while keeping the attractive commercial capabilities of SACs [37].

Thermogelling polymers

Often, polymers and plastics appear in the IUPAC Top Ten lists. Since the beginning of the 20th century, these materials have become ubiquitous and offer solutions to remediate environmental pollution. Innovations in polymer science usually boost the materials' sustainability, as well as unveil unforeseen applications. Thermogelling polymers present the perfect example. These smart materials transition from liquid to gel with the pull of a single trigger—temperature. There is no need for chemical crosslinkers or supplementary stimuli. This property has catapulted applications in cosmetics, medical imaging, drug delivery, and bioengineering—particularly in the production of artificial tissues for regeneration [38]. Most of these applications stem from the versatility of thermogelling polymers, often designed with biocompatibility in mind. Normally, temperature triggers the transformation of linear copolymers into micelles first, then into more complex networks, which eventually evolve into a stable gel. A key advantage for biomedical applications is injectability. As liquids, or *sols*, these substances are easily inserted into the body, where they spontaneously, but progressively transition into the gel state. In drug delivery, for example, the gels enable the sustained release of active ingredients into the affected zones, with very promising results in complex diseases, including cancer [39]. The starting state as *sols* also enables interesting uses in 3D printing, an ideal platform to prepare biocompatible scaffolds for wound regeneration, cell cultures or organoid growth [40]. Perhaps the most promising and positive result in the field is related to the versatility of thermogelling polymers for real-life repair of tissues in the eye. Until recently, the vitreous





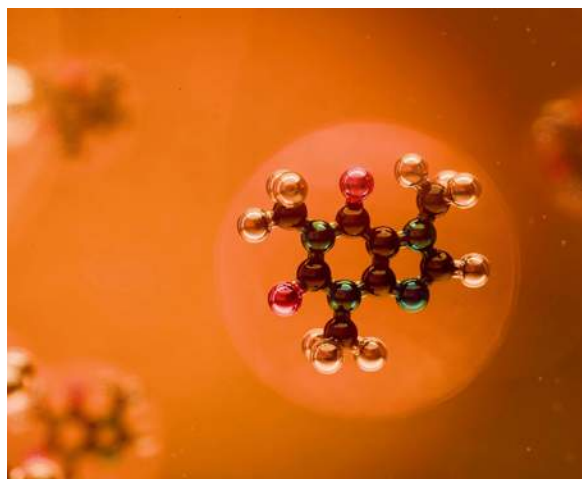
humour was considerable irreparable and irreplaceable if damaged. This issue caused retinal diseases and even detachment, often resulting in permanent blindness. However, researchers crafted a solution to repair retina detachments, mimicking the special structure and characteristics of the vitreous humour with thermogelling polymers of similar viscosity and transparency. In time, the gel stimulates and supports structures naturally present in the eyes, such as collagen, fibrillin, and vitrin, overall reducing the complications associated with retinal surgery [41]. Nowadays, some start-ups investigate the possibilities of these polymers in clinical and commercial applications, while researchers explore areas such as 3D bioprinting, soft robotics, and environmental sensing [42].

Additive manufacturing

It is usually said that Renaissance artist Michelangelo simply “saw” his statues inside blocks of marble, then stripped the excess away to create pieces of art such as his statue of David in Florence, Italy. Additive manufacturing is the exact opposite process. It consists of creating objects layer by layer, in an additive manner, minimising material waste. Often, “additive manufacturing” means 3D-printing, because of the possibilities of polymer and plastic printing in manufacturing, but other techniques also have an additive approach at the core and could count in the same category [43]. Chemistry is crucial to increasing the sustainability of additive manufacturing even further. This involves innovations in materials science to produce printable polymers, ceramics, and biobased materials with better biodegradability and recyclability. It also involves the development of sustainable solutions in inks, resins, and filaments to make manufacturing itself more resilient and energy efficient [44]. These discoveries have driven developments such as additive manufacturing of metals, using composite polymers and metal powders. This increases

the efficiency compared to current alternatives, as well as reduces the production of waste, since the unused solution is easily recycled. Moreover, the most recent advances in 3D-printing open possibilities in the production of hollow, yet strong structures, such as scaffolds and lattices. The optimisations in engineering could contribute to the creation of lighter components, especially useful in the manufacturing of machinery. In this scenario, additive manufacturing would boost sustainability by reducing the amount of materials needed, as well as making lighter cars and planes, cutting carbon emissions throughout the lifetime of the product [45]. This technology could increase the sustainability of chemistry itself, by creating applications for researchers and innovators in the lab. Additive manufacturing could contribute to the creation of more sustainable lab equipment, as well as accelerate scale-up with the 3D-printing of low-cost prototypes and developmental demonstrations. Moreover, most designs for parts are published in repositories in open access, fostering not only a quicker implementation of innovation, but also a more collaborative ecosystem for chemists worldwide [46]. Large companies such as Evonik, Airbus, and Carbon have reportedly started working in additive





manufacturing, contributing to cutting CO₂ emissions and catalysing commercial uptake.

Multimodal foundation models for structure elucidation

Artificial Intelligence (AI) has become a buzzword, in some cases carrying negative connotations because of its impact on the environment. Nevertheless, some interesting applications of AI could make chemists' lives easier, by accelerating analytic processes as well as reducing the hindrance of repetitive tasks, which opens up time for creativity, as discussed in the Top Ten selection of 2020 [47]. This is exactly the case of molecular models for structure elucidation, a technology that makes the most of machine learning, deep learning, and artificial intelligence to holistically study spectra from different sources, such as infrared, nuclear magnetic resonance, UV spectroscopy, and mass spectrometry, among others. In contrast, common approaches previously focused on single spectroscopic techniques. The "multi-modal" approach presents several advantages, rooted in the interconnectivity of data to provide the algorithms with a structural understanding of molecules and materials. For example, this could cut costs in laboratories with limited access to expensive equipment and databases, since simple experiments, such as infrared measurements, would suffice for structure elucidation. The model would match the selected spectra with available datapoints, comparing across complex patterns and accelerating assignment of an optimal structure [48]. Besides democratising elucidation, these multimodal models could also accelerate drug discovery and materials innovation, as well as optimise processes in pollution monitoring, quality control, and forensic analysis. The models use publicly-available databases, including patent data, to train the algorithms

with standardised sources [49]. Although incipient, the idea has already attracted the interest of companies such as IBM. The existing models still lack the reasoned and creative approaches of trained chemists, but the investment in innovation, including better interpretation of structures with standards such as InChI and SMILES, will only make models better. Soon, AI will also reduce the struggles of structural elucidation.

Direct air capture

We must tackle the climate crisis with every available alternative. And, although often discredited as a temporary patch, direct air capture (DAC) is widely recognised as a strategic solution to reduce the concentration of carbon dioxide in the atmosphere and mitigate the effects of climate change [50]. Chemistry is central to solving the principal problem of DAC—successfully sequestering a substance present as the smallest atmospheric proportion of four hundred parts per million. This concentration is enough to cause climate alterations, but sufficiently minuscule to make materials efficient enough for carbon capture. To overcome this, chemists encountered two complementary courses of action. The first relies on reactive adsorption, using basic compounds such as hydroxides, oxides, borates, and amines to "trap" carbon dioxide, usually in the form of carbonates and similar salts. In most cases, the main downside is the demand of energy needed for regeneration, a process that requires really high pressure and temperature. The second idea counts on a technology from the original Top Ten list in 2019—metal organic frameworks (MOFs). Structured like miniaturised sponges, MOFs are porous materials with an extremely high adsorption surface, which makes them ideal to selectively store gases, included CO₂. Usually, the efficiency trapping carbon dioxide is lower for physical than chemical sorbents, but regeneration is easier and smoother, which in turn makes MOFs more





attractive for industrial implementation. Of course, chemists have also studied a consolidated solution – decorating the extensive surface of metal-organic frameworks with reactive structures, such as amines. This strategy improves the adsorption capacity, as well as makes MOFs even more selective towards carbon dioxide versus other gases in the atmosphere [51]. Most MOF-based solutions have progressed to pilot plants, even industrial demonstrations [52]. And, in general, DAC has already established itself as an alternative for carbon capture worldwide. There are several industrial infrastructures with high levels of maturity, that have cut the cost below \$100 per ton of CO_2 surpassing the most optimistic predictions by the International Energy Agency. However, some studies suggest that the solutions lack scalability and resilience [53], supported by news of closures and cuts among leaders such as Climeworks and Ørsted. While carbon capture could contribute to our climate-neutral targets, the technology still needs further development and improvement to become competitive [54].

Electrochemical carbon capture and conversion

While DAC offers an opportunity to capture carbon dioxide directly from the atmosphere, electrochemistry enables an extra step—using CO_2 as an alternative source of carbon, converting it into chemicals, fuels, and other value-added products. The first examples of electrochemical carbon capture date back to the 1960s and 70s, when they were used as a tool to complement the methods based in adsorption. Using electricity as the driving force usually reduces cost and enables coupling

with clean sources of energy, such as solar, wind, and hydrothermal. Additionally, electrochemical processes tend to surpass the performance of traditional thermochemical alternatives, reducing the overall impact and making them an attractive alternative to DAC [55]. Additionally, electrochemistry enables efficient liberation of CO_2 gas, which is less energetically demanding than desorption processes. Moreover, electrochemistry offers the chance to seamlessly couple capture with conversion and utilisation. Once trapped, carbon dioxide serves as a source of carbon towards key chemical feedstocks, including carbon monoxide (CO), formate, methanol, ethylene, as well as longer hydrocarbons [56]. In the past few years, an increasing number of studies showcased the limitless possibilities of electrochemical carbon dioxide reduction reactions, usually referred to as eCO₂RR [57]. Since the first example of eCO₂RR, published in 1985 [58], the advances in catalysis, materials science, and engineering have perfected the processes to prepare small feedstock molecules, breaking ground for more challenging reactions, such as the synthesis of hydrocarbons [59]. In this area, electrocatalysts made of abundant metals such as copper and nickel have shown great promise, converting carbon dioxide to both linear and branched hydrocarbons with chains of up to six carbon atoms [60]. As a relatively recent field, eCO₂RR is still far from competitive to the traditional thermochemical processes in oil refining. However, the reliance on electricity as the sole source of energy increases sustainability, as well as democratises and delocalises access to chemicals. Despite its early stage, far from scalability and industrial applications, the electrocatalytic conversion of

carbon dioxide is still regarded as a promising alternative to produce value-added chemicals in a sustainable manner [61]. Overall, electrochemistry is an emerging technology for both capture and conversion of carbon dioxide. Nevertheless, its promise to promote sustainability and circularity, mitigating the impact of climate change, is clear. Further research will undoubtedly unveil and uncover interesting innovations to transform CO₂ from waste into feedstock, making it a key starting material for manufacturing in the chemical industry [62].

Conclusions

In its seventh consecutive year of operation, the IUPAC Top Ten Emerging Technologies in Chemistry initiative continues to look into sustainability and circularity, connecting new and innovative ideas towards a greener future [63], while maintaining a strong interest in the development of methods for the improvement of human health. Overall, the selection of the 2025 Top Ten, carefully crafted by a panel of experts from a pool of global nominations, continues to carry the spirit established by the first Top Ten list released in 2019 and that is to highlight the potential of chemistry—and chemists—to provide solutions to the most urgent societal issues. The initiative attempts to highlight diverse technologies from around the world that are in early stages of development in order to boost their visibility and eventually facilitate technology transfer and market uptake. This edition expands the selection to seventy technologies, showcasing the versatility and variability of creativity in chemistry. IUPAC's objective in putting these highly-innovative ideas under the spotlight is to strongly encourage collaboration across all scientific disciplines in order to accelerate progress towards a more sustainable and equitable world.

Acknowledgments

The author would like to thank everyone who contributed with ideas and submissions to the 2025 edition of the "Top Ten," as well as the jury of experts that made the final selection, including: Ehud Keinan, Javier García Martínez, Arasu Ganesan, Molly Shoichet, Julianne Sempionatto, Mamia El-Rhazi, Jorge Alegre Cebollada, Bernard West, Natalia Tarasova, Zhigang Shuai, Rai Kookana, and Kira Welter. Special thanks to Michael Dröscher for not only serving on the jury, but also for coordinating this initiative since its inception in 2019 and to Fabienne Meyers for all the support and patience with the editorial process. And, of course, massive thanks to Bonnie Lawlor, for her infinite patience organising the calls, keeping the minutes, and revising this manuscript to notably improve its readability and quality. 

References

- (a) F. Gomollón-Bel. *Chem. Int.* 2019, 41, 2, 12, DOI: 10.1515/ci-2019-0203. (b) <https://iupac.org/what-we-do/top-ten/>
- F. Gomollón-Bel, J. García-Martínez. *Nat. Chem.* 2022, 14, 2, 113, DOI: 10.1038/s41557-021-00887-9.
- F. Gomollón-Bel, J. García-Martínez. *ACS Cent. Sci.* 2025, 11, 6, 819, DOI: 10.1021/acscentsci.5c00530.
- C. Caldeira et al. "Safe and sustainable by design chemicals and materials." European Commission JRC (2022). DOI: 10.2760/879069
- M. Regehy et al. *Nature*, 2020, 588, 7839, 620, DOI: 10.1038/s41586-020-3029-7.
- C. Q. Choi. "3D-printing hollow structures with xolography". *IEEE Spectrum*, 28 December 2020. Accessed 17 July 2025. Link: <https://spectrum.ieee.org/xolography-printing>
- P. Nunez Bernal et al. *Nat. Rev. Mater.* 2025, DOI: 10.1038/s41578-025-00785-3
- Z. Hussain. "Xolography—The Latest Innovation in 3D Printing". Engineering.com, 22 January 2021. Accessed 17 July 2025. Link: <https://www.engineering.com/xolography-the-latest-innovation-in-3d-printing/>
- L. Stüwe et al. *Adv. Mater.* 2023, 36, 4, 2306716, DOI: 10.1002/adma.202306716.
- N.F. König et al. *Adv. Mater.* 2025, 37, 5, 2413391, DOI: 10.1002/adma.202413391.
- Xolo (2023). Accessed 17 July 2025. Link: <https://xolo3d.com/about/>
- The Nobel Prize (2023). Accessed 17 July 2025. Link: <https://www.nobelprize.org/prizes/chemistry/2023/summary/>
- S.E. Elugoke et al. ACS Symposium Series, Vol. 1465. DOI: 10.1021/bk-2024-1465.ch001
- S. Ashok Kumar et al. *Mater. Adv.* 2023, 4, 18, 3951, DOI: 10.1039/D3MA00254C.
- M. Jorns, D. Pappas. *Nanomaterials* 2021, 11, 6, 1448, DOI: 10.3390/nano11061448.
- (a) N. Panwar et al. *Chem. Rev.* 2019, 119, 16, 9559, DOI: 10.1021/acs.chemrev.9b00099. (b) Z. Yhang et al. *Chem. Rev.* 2023, 123, 18, 11047, DOI: 10.1021/acs.chemrev.3c00186.
- A. Döring et al. *Light Sci. Appl.* 2022, 11, 1, 92, DOI: 10.1038/s41377-022-00764-1.
- I.M. Feigel et al. *J. Mat. Chem.* 2011, 21, 25, 8940, DOI: 10.1039/c1jm10521c.
- S. Kralj, S. Marchesan. *Pharmaceutics* 2021, 13, 8, 1262, DOI: 10.3390/pharmaceutics13081262.
- Q. Xiong et al. *Nat. Commun.* 2018, 9, 1, 1743, DOI: 10.1038/s41467-018-04172-1.
- Z. Zhang et al. *Angew. Chem. Int. Ed.* 2021, 60, 45, 24234, DOI: 10.1002/anie.202109985.
- E. Karatahnasis, K.B. Ghaghada. Wiley Interdiscip. Rev.: Nanomed. *Nanobiotechnol.* 2016, 8, 5, 678, DOI: 10.1002/wnan.1387.
- W. Jiang et al. *ACS Nano* 2022, 16, 10, 15705, DOI: 10.1021/acsnano.2c06104.

24. C.P. Pilkington et al. *Nat. Chem.* 2024, 16, 10, 1612, DOI: 10.1038/s41557-024-01584-z.
25. W. Wang et al. *Angew. Chem. Int. Ed.* 2025, 64, 11, e202421827, DOI: 10.1002/anie.202421827.
26. C.A. Hutchinson et al. *Science* 2016, 351, 6280, aad6253, DOI: 10.1126/science.aad6253.
27. A. Guan et al. *Biotechnol. Adv.* 2024, 73, 108366, DOI: 10.1016/j.biotechadv.2024.108366.
28. Q. Xu et al. *Mater. Today Bio* 2023, 23, 100877, DOI: 10.1016/j.mtbio.2023.100877.
29. (a) S. Razavi et al. *Sci. Adv.* 2024, 10, 24, adk9731, DOI: 10.1126/sciadv.adk9731. (b) S. Mukwaya et al. *Commun. Chem.* 2021, 4, 1, 161, DOI: 10.1038/s42004-021-00597-w.
30. S. Mitchell, J. Pérez-Ramírez. *Nat. Commun.* 2020, 11, 1, 4302, DOI: 10.1038/s41467-020-18182-5.
31. M.A. Bajada et al. *Cell Rep. Sustain.* 2025, 2, 1, 100286, DOI: 10.1016/j.crsus.2024.100286.
32. S.K. Kaiser et al. *Chem. Rev.* 2020, 120, 21, 11703, DOI: 10.1021/acs.chemrev.0c00576.
33. C.E. Creissen, M. Fontecave. *Nat. Commun.* 2022, 13, 1, 2280, DOI: 10.1038/s41467-022-30027-x.
34. (a) S. Back et al. *Chem. Sci.* 2016, 8, 2, 1090, DOI: 10.1039/C6SC03911A. (b) S. Mitchell et al. *Angew. Chem. Int. Ed.* 2018, 57, 47, 15316, DOI: 10.1002/anie.201806936.
35. A. Extnance. "Single-atom catalysis." *Chemistry World*, 21 October 2019. Accessed 19 July 2025. Link: <https://www.chemistryworld.com/features/single-atom-catalysis/3010930.article>
36. Z. Chen et al. *Nat. Nanotech.* 2018, 9, 1, DOI:
37. T.A. Gazis et al. *ACS Catal.* 2025, 15, 9, 6825, DOI: 10.1021/acscatal.4c07405.
38. S. Qiao, H. Wang. *Nano Res.* 2018, 11, 10, 5400, DOI: 10.1007/s12274-018-2121-x.
39. M. Chen et al. *Small* 2021, 17, 52, 2104773, DOI: 10.1002/smll.202104773.
40. H.A. Pearce, A.G. Mikos. *Curr. Opin. Biomed. Eng.* 2022, 24, 100412, DOI: 10.1016/j.cobme.2022.100412.
41. (a) "New polymer gel for treating blindness." *Nature India*, 9 April 2019. Accessed 19 July 2025. Link: <https://www.nature.com/articles/nindia.2019.44>. (b) Z. Liu et al. *Nat. Biomed. Eng.* 2019, 8, 3, 598, DOI: 10.1038/s41551-019-0382-7.
42. Q. Lin et al. *Acc. Mater. Res.* 2021, 2, 10, 881, DOI: 10.1021/accountsmr.1c00128.
43. R. Linke. "Additive manufacturing, explained." MIT Sloan School, 7 December 2017. Accessed 19 July 2025. Link: <https://mitsloan.mit.edu/ideas-made-to-matter/additive-manufacturing-explained>
44. E. Sanchez-Rexach et al. *Chem. Mater.* 2020, 32, 17, 7105, DOI: 10.1021/acs.chemmater.0c02008.
45. N. Nagabandy. "How 3D Printing Can Dramatically Reduce Carbon Emissions in the Manufacturing Industry". *Manufacturing Tomorrow*, 6 September 2023. Accessed 19 July 2025. Link: <https://www.manufacturingtomorrow.com/story/2023/05/how-3d-printing-can-dramatically-reduce-carbon-emissions-in-the-manufacturing-industry/20720/>
46. O. A. Alimi, R. Meijboom. *J. Mater. Sci.* 2021, 56, 16824, DOI: 10.1007/s10853-021-06362-7.
47. F. Gomollón-Bel. *Chem. Int.* 2020, 42, 4, 3, DOI: 10.1515/ci-2020-0402.
48. M. Alberts, et al. *arXiv* 2024, DOI: 10.48550/arXiv.2407.17492.
49. Y. Su et al. *arXiv* 2025, DOI: 10.48550/arXiv.2508.08441.
50. IEA (2022). "Direct air capture: a key technology for net zero." IEA, Paris, April 2022. Accessed 24 July 2025. Link: <https://www.iea.org/reports/direct-air-capture-2022>
51. (a) E.S. Sanz-Pérez et al. *Chem. Rev.* 2016, 116, 19, 11840, DOI: 10.1021/acs.chemrev.6b00173. (b) X. Zhu et al. *Chem. Soc. Rev.* 2022, 51, 15, 6574, DOI: 10.1039/D1CS00970B.
52. X. Zhang et al. *Carbon Capture Sci. Tech.* 2023, 9, 100145, DOI: 10.1016/j.ccst.2023.100145.
53. F. Bisotti et al. *Chem. Eng. Sci.* 2024, 283, 119416, DOI: 10.1016/j.ces.2023.119416.
54. M. Burke. "Warning that carbon capture not a silver bullet for climate change." *Chemistry World*, 8 September 2022. Accessed 24 July 2025. Link: <https://www.chemistryworld.com/news/warning-that-carbon-capture-not-a-silver-bullet-for-climate-change/4016198.article>
55. A.M. Zito et al. *Chem. Rev.* 2023, 123, 13, 8069, DOI: 10.1021/acs.chemrev.2c00681.
56. I. Sullivan et al. *Nat. Catal.* 2021, 4, 11, 952, DOI: 10.1038/s41929-021-00699-7.
57. Y.C. Li. *Commun. Chem.* 2024, 7, 1, 48, DOI: 10.1038/s42004-023-01096-w.
58. Y. Hori et al. *Chem. Lett.* 1985, 14, 11, 1695, DOI: 10.1246/cl.1985.1695.
59. J. Han et al. *Chem. Sci.* 2024, 15, 21, 7870, DOI: 10.1039/D4SC01931H.
60. (a) D.-J. Liu. *Joule* 2022, 6, 9, 1978, DOI: 10.1016/j.joule.2022.08.012. (b) Y. Zhou et al. *Nat. Catal.* 2022, 5, 6, 545, DOI: 10.1038/s41929-022-00803-5.
61. (a) D. Xu et al. *Carbon Energy* 2022, 5, 1, e230, DOI: 10.1002/cey2.230. (b) G. Leonzio et al. *Chem. Eng. Res. Des.* 2024, 208, 934, DOI: 10.1016/j.cherd.2024.07.014.
62. I. Ghat et al. *J. CO₂ Util.* 2025, 95, 103075, DOI: 10.1016/j.jcou.2025.103075.
63. F. Gomollón-Bel, J. García-Martínez. *Chem. Sci.* 2024, 15, 14, 5056, DOI: 10.1039/D3SC06815C.

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