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A market for metal–organic frameworks

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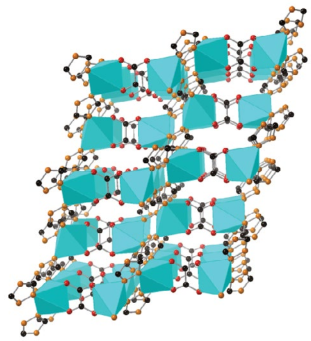
The sorption and storage properties of metal–organic frameworks are extensively reported but their commercialization has been slow. Collaborative efforts from scientists, engineers and investors are needed to accelerate the transition from laboratory to the marketplace.

A material typically has a complex and unpredictable journey to become a commercial product. The challenges that scientists and engineers face require input from experts on synthesis and characterization, processing, scale-up, manufacturing and registration, as well as on the specific requirements of the application, such as fluid dynamics, conductivity or toxicity, to name a few. Also, gaining funding and financial backing from private investors for fundamental research and applied development is not easy to achieve. There is also the element of identifying and tackling the right problem, at the right time.

For metal–organic frameworks (MOFs), their porous structures are key to the separation, storage or delivery capabilities that make them appealing for a broad range of applications. These pores can be tuned in size or chemical functionality to establish the optimal performance in gas sorption or in the adsorption of small molecules from liquids. Other properties of MOFs, such as crystal size, surface area and the type and location of defects, have roles in determining their use, in particular, as heterogeneous catalysts. In this issue of *Nature Materials*, a Perspective by William Morris and co-authors details the necessary steps for MOFs – irrespective of the target application – to transition from the research laboratory to commercial use. Highlighting that there is only a handful of commercial products compared with the, at least, 100,000 structures synthesized so far, it is evident that challenges exist at different stages in the process. By breaking the journey from laboratory to market into five sections – synthesis, forming, processing, prototyping and compliance – Morris and co-authors aim to identify an approach to help commercialize MOFs in various applications.



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For commercial use, a MOF must be manufactured at scale, with forming of the synthesized MOF being a critical step. Forming entails the preparation of pellets, thin films, beads or granules from a powdery material and must occur without altering the surface area and other parameters of the material. Morris and co-authors state that costs to produce MOFs are high compared with other solid adsorbents, although costs reduce with scale up. There is also a call for prototype production at early stages of research, enabling performance to be evaluated in real-world conditions and a rigorous techno-economic analysis of the product. The techno-economic analysis encompasses the costs and revenues associated with a product, giving an indication of when a company based on the technology may become profitable.

Companies with an interest in MOF technologies started arriving on the scene in 2011 with framergy (USA) and have now reached an approximate number worldwide of 50. Many of these companies are focused on CO_2 capture, including but not limited to Svante (Canada), Nuada (USA), Avnos (USA), Mosaic (USA), Captivate Technology (New Zealand) and AspiraDAC (Australia). The technologies driving these companies forward involve MOFs of differing composition and various methods to regenerate the active materials. In one example, a MOF licensed by Svante – zinc-based Calgary Framework 20 (CALF-20) (pictured) – captures CO_2 from wet acid flue gas and relies on an injection of low-pressure steam to desorb the CO_2 captured[1]. In 2023, when used in a cement plant in Richmond, Canada, CALF-20 reportedly removed about 1 tonne of CO_2 per day from flue gas. The scaled-up production of CALF-20 for Svante has been achieved by BASF (Germany), on a scale of several hundred tonnes per year.

Another MOF application is water harvesting[2], with companies including WaHa (USA), AirJoule (USA) and Transaera (USA). The lower release temperature for water compared with silica and zeolites makes MOFs more efficient at obtaining water from the atmosphere. Some of the most effective MOFs for water harvesting are aluminium-based MOFs (MOF-303) that can generate 0.7 litres per kg_{MOF} per day in desert conditions[3].

The removal or storage of hazardous gases are other possible applications of MOFs, with companies active in this area including MOFapps (Norway), SquairTech (France) and Numat (USA). MOFapps is developing zirconium-based MOFs to remove toxic gases in defence settings or for use in air filters, and SquairTech uses aluminium-based MOFs for the targeted removal of formaldehyde from air. In manufacturing plants, Numat is producing MOFs on a scale greater than a hundred tonnes per year that can be used to store gases in cylinders sub-atmospherically. These gases include arsine, phosphene and boron trifluoride for use in the electronics industry.

More recently, artificial intelligence and machine learning is driving MOF commercialization with interest from several start-ups and large companies, including Orbital Materials (USA), Cusp.AI (UK) and IBM (USA). These ventures, alongside companies focused on the scaling up of MOFs, such as Promethean Particles (UK) and novoMOF (Switzerland) as well as some mentioned above, will be key to the accelerating MOF commercialization.

As the global population looks to reduce greenhouse gas emissions, consume less energy and alleviate water scarcity, MOFs are poised to help in these vital areas. There is now more impetus than ever to bridge gaps in funding and encourage the translation of fundamental research in academic laboratories to increase the pool of useful MOFs.

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