Creating New Materials, Solving World Problems – One MOF at a Time

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Imagine an autumn day in the not-so-distant future. At the Mauna Loa Observatory in Hawaii, a historic event is taking place. For the first time since measurements began in the mid-20th century, the values concerning atmospheric change continue to drop. Whereas they would normally rise again after the end of the summer due to seasonal effects, the downward trend now persists. The observations make world news, with headlines across global media announcing the beginning of the end of the climate crisis. «We did it. We fixed the climate» some leaders already proclaim.

It could be the premise for a science fiction story. Yet, it is not entirely fiction. Capturing CO_2 – the main greenhouse gas – from the air is technologically possible. So, in principle, the excess CO_2 in the atmosphere, which largely drives today's climate change as we have been pumping it in since the Industrial Revolution, could also be removed. This means the current concentration of over 427 parts per million (ppm) could be brought down to a lower value, for example, to 310 ppm, the level when daily CO_2 measurements began at the Mauna Loa Observatory. It would be as if we are rewinding the climate's history by several decades.

The Keeling Curve and the observatory in Hawaii have, in their seventy-year existence, become symbols of the climate. They are its pulse. So, a halt and reversal of global warming would first be manifest there. Maybe this will remain a vain hope, but maybe not. Human ingenuity is powerful – so powerful that, in theory, it could undo historic climate emissions.

The way to restore the climate to its pre-industrial state – or almost – is by capturing CO_2 and other greenhouse gases like methane from the air

on a massive scale. The technology for this essentially already exists, and is already in use. In Iceland, direct air capture, or DAC, is already in execution with several installations powered by the abundant geothermal energy there. Fans draw in air, which is then stripped of CO_2 in collectors. The captured greenhouse gas is then released by heating – again using geothermal energy – and injected deep underground to be stored there permanently. These installations reportedly have a capacity of several tens of thousands of tons of CO_2 per year.
That may sound like a lot, but it is only a tiny fraction of the fresh CO_2 – primarily coming from the burning of fossil fuels – that still enters the atmosphere annually. Nevertheless, the technology is promising, especially because there's room for improvement – as always. Here MOFs, materials with enormous potential, enter the scene. When it comes to capturing CO_2 from the air, like DAC, MOFs could spark a revolution in this field. They could truly make negative emissions – the active removal of greenhouse gases from the atmosphere – a key player in the fight against climate change. And they do all this with materials that, outwardly, look like nothing more than a heap of powder.
MOF stands for metal-organic framework. It is not just one material, but a whole class of them – there are already 100,000 which have all been created in chemical laboratories in recent years. They are artificial and, in that sense, demonstrate what chemistry can achieve. MOFs are designed and created from the bottom-up, with the desired functionalities. It is almost like building with Lego blocks – you can build these new materials in the form of molecular structures as you please. Furthermore, they can often be produced in large quantities.
Chemists have known about MOFs for some time, but on 8 October 2025, the whole world suddenly found out about them. On that day, the Nobel Prize in Chemistry was awarded to three MOF pioneers: Richard Robson, Susumu Kitagawa, and Omar Yaghi. They thus shared the highest distinction in science for their development of – in the words of the Nobel Committee – «a new type of molecular architecture». And with that, the Swedes followed in the footsteps of the Italians and the Swiss, who awarded the Balzan Prize for Nanoporous Materials for Environmental Applications to Omar Yaghi in 2024.
What makes MOFs so special? What gives them so much potential? Their particular «molecular architecture», to use the Nobel Committee's words. MOFs are extremely porous. Built from metal ions and organic molecules, they are compounds with a regular, crystal-like structure that is very hollow – actually more empty than full. This

allows the MOFs to house other molecules – absorbing, holding, and releasing them, like microscopic sponges. These sponges are also very stable; they can withstand high temperatures and be reused. Last but not least, chemists can custom design them to fit the specific type of molecules they want them to absorb.

To illustrate the extremely porous nature of MOFs, in 1999, Omar Yaghi stunned his colleagues when he presented MOF-5, as this milestone material was called, where just a few grams have an internal surface area (calculating all the cavities combined) as large as a soccer field. So that is how a macroscopic dimension can be rolled up to the microscopic level.

Since the turn of the century, chemists have been designing and producing MOFs for specific target molecules. MOF-303, for example, absorbs water molecules from the air. MIL-101 can absorb oil particles or antibiotic molecules and subsequently break them down. MOFs can also serve as catalysts. UiO-67, in turn, has a preference for PFAS, the family of «forever chemicals» that have been in the news so much in recent years. NU-1501 stores hydrogen without the need for intense cooling, which makes transporting difficult. ZIF-8 filters rare earth metals from wastewater. Finally, CALF-20 absorbs CO_2.

There we are again with CO_2 – the main culprit behind the current climate crisis. CALF-20 is already used in cement factories to capture greenhouse gases from flue gas, after which it can be stored underground, as in the Icelandic DAC installations. But it is not the only MOF that can capture CO_2 from the air. There are more, and new ones are constantly being developed – remember, the total number of MOFs stands at 100,000. At the end of 2024, Omar Yaghi again made headlines with his invention of a material especially suited for DAC. Enter COF-999, a sibling of MOFs: the metal ions are replaced by organic components, but the principle is the same. The material has cavities that are tailor-made to house CO_2 molecules. Moreover, COF-999 is particularly stable, water-resistant (which is important outdoors), and it can be reused many times.

Two hundred grams of COF-999 could capture twenty kilograms of CO_2 from the air annually – about as much as one tree could. Outdoors on their university campus at the University of California – Berkeley, Yaghi’s team demonstrated that it takes two hours for the material to become fully saturated with CO_2. Then, heating it to 60 degrees is enough to release the molecules again (for example, for storage), after which a new cycle can begin.

This CO_2 uptake by COF-999 happens automatically; only a little heat is needed to release it, and the material is so stable that it is a formidable competitor to the materials currently used in DAC installations. In cases where those installations are not making a significant difference, they could do so in the future if equipped with the right MOFs. So going back to that autumn day imagined at the beginning of this article, negative emissions really could become a weapon in the fight against climate change.

In the meantime, the MOF field is buzzing with activity. New MOFs are being developed almost daily, and each has specific target molecules and specific applications. So while the world-changing potential of MOFs is already enormous, it continues to grow. To end with the words of the Nobel Committee, MOFs might very well become the materials of the 21st century.