Our engineering team is making versatile, tiny sensors from the Nobel-winning ‘metal-organic frameworks’

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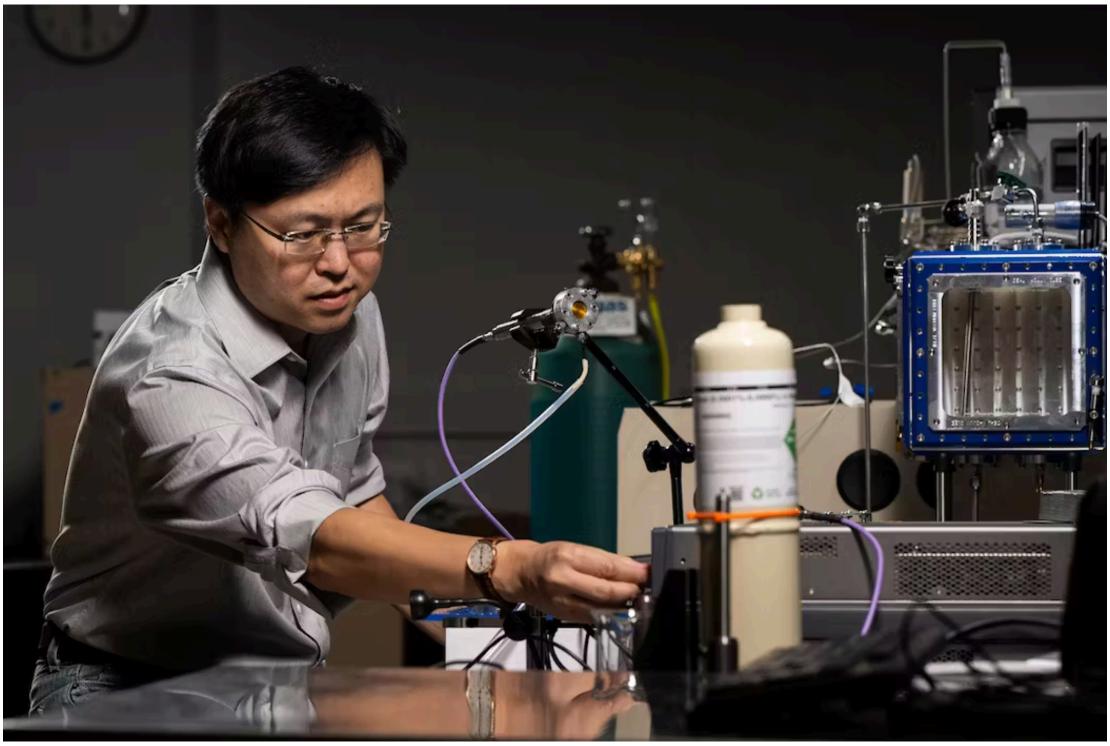
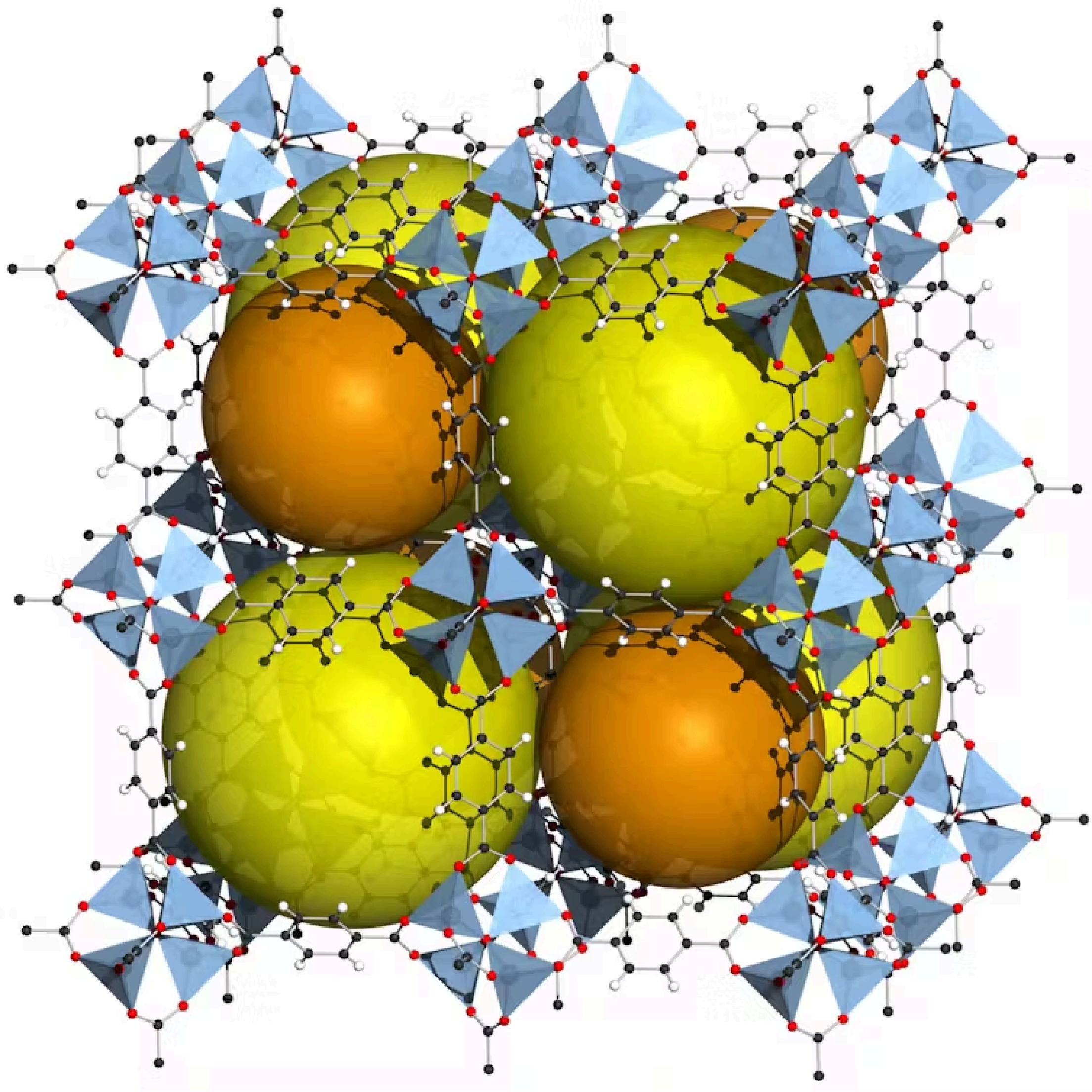


Prof. Jie Huang stands with the MOF-based breathalyzer his lab developed with support from the NIH.
Michael Pierce/Missouri S&T

When the 2025 Nobel Prize in Chemistry honored Omar Yaghi – the “father of metal-organic frameworks,” or MOFs – along with Susumu Kitagawa and Richard Robson, it celebrated more than the creation of a new class of crystalline materials. It recognized a revolution quietly reshaping how scientists capture, store and sense molecules. These MOFs could allow for sensor technologies that make workplaces, the environment and human bodies safer.

What are MOFs, and why do they matter?

MOFs are made by linking metal ions – atoms that carry an electrical charge – with organic molecules, the carbon-based building blocks found in most living things. Together they form tiny, sponge-like structures full of microscopic pores. You can imagine them as an atomic-scale scaffold filled with nano-sized rooms, each precisely engineered to host certain molecules like guests.



Metal-organic frameworks, such as MOF-5 shown here, have metal components, organic 'linkers' and a cavity that can allow in gases.

Because chemists can mix and match different metals and organic linkers, there are thousands of possible MOFs – each with unique properties. Depending on how they're structured, some have so much internal surface area that a single gram could cover a football field.

This sponge-like porosity – meaning lots of tiny holes inside – lets MOFs trap and release gases, store energy-rich fuels like hydrogen, and capture harmful pollutants. MOFs can use a variety of chemicals in their structure, which lets researchers fine-tune how strongly an MOF interacts with specific molecules.

These features have already inspired potential uses such as capturing carbon dioxide from the air to reduce greenhouse gas concentrations in the atmosphere, pulling clean water from humid air, and delivering medicines inside the body. Over the past decade, the unique properties of MOFs have also opened new possibilities for sensing and detection.

Since 2016, our team of engineers has been developing MOF-based sensors that can detect certain gases and vapors in an environment in real time. These materials' unique properties are opening new possibilities for sensing in health, safety and environmental monitoring.

From a storage material to a sensing material

When an MOF takes in gas or liquid molecules, its tiny framework changes ever so slightly: It may change in size, how it bends light, or how it conducts electricity, depending on what and how many molecules it absorbs.

By connecting MOFs to devices that can sense changes in light or electricity, researchers can turn these tiny shifts into measurable signals such as light, frequency or voltage. The signals then reveal what chemical is present and how much of it there is. In simple terms, when molecules enter or leave the MOF's pores, they slightly change how light travels through it or how electricity behaves around it, and those changes become the sensor's readable output.

Our group at Missouri University of Science and Technology has developed several kinds of MOF-based sensor platforms. Across all these platforms, the core idea is the same: MOFs act as selective sponges that temporarily hold certain gas molecules in their tiny cages, and our devices measure the timing and amount of this uptake and release.

In one study, we attached a single crystal of a copper-based MOF called HKUST-1 to the smooth, flat end of a cut optical fiber – the same kind of thin glass strand used to carry internet and phone signals.

This crystal-fiber combination worked as a tiny device that could measure how light waves interfere with each other. As nearby gas molecules moved into the tiny pores of the MOF crystal, the way it bent and reflected light changed slightly. The optical fiber – connected to a light source and detector – picked up these changes, allowing us to see in real time how many gas molecules the material was taking in.

Our probes show not just that gas molecules enter the tiny cages of the MOF, but also how fast they come and go. By measuring both the amount and the speed of adsorption and release, we can tell which molecules are being taken up and in what proportion, when several are present together. This dynamic view helps us see, in real time, how the material selects one target gas over others. It turns adsorption into a measurable, useful signal for sensing and identification.

In health care, an MOF can act like a selective sponge for specific breath molecules that indicate real, measurable diseases. For example, an MOF designed to adsorb acetone can capture and concentrate this gas from exhaled breath. Acetone levels rise above normal values in people with diabetic ketoacidosis, allowing the sensor to clearly and quantitatively detect the disease.

Prof. Jie Huang and his team at Missouri S&T developed an MOF–based breath sensor, funded by the NIH, that was developed for COVID-19 and can also be employed for detecting disease biomarkers such as acetone and ammonia in exhaled breath.
Michael Pierce/Missouri S&T

Likewise, an MOF that selectively adsorbs ammonia can concentrate this compound from exhaled breath. Ammonia levels increase above normal values in people with chronic kidney disease, so the sensor can provide a definite indicator of reduced kidney function. Integrating such MOFs into sensor hardware would allow for sensitive, noninvasive screening for these two diseases, based on quantifiable breath markers.

Coating a material in a thin layer of MOFs can take hours. But recently, we developed a quick and simple “droplet-drying” method that forms a crystal layer of the copper-based MOF HKUST-1 directly onto the end of an optical fiber in under two minutes. The resulting film, only about 1/20th the width of a human hair, acted as a high-performance gas sensor that detected humidity, ethanol or carbon dioxide in the environment within seconds.

We also combined MOFs with a hand-held metal device that can sense changes in microwave signals – a bit like how a radio antenna picks up invisible waves in the air. When gas molecules entered the MOF layer, they slightly changed how the device responded to those waves, allowing it to detect gases with remarkable sensitivity.

This sensor made for a low-cost, portable device that could tell one kind of gas molecule apart from another, rather than just detecting that some gas is present. It's like having a nose that can tell apples from oranges, not just detect that something smells fruity.

Our research suggests that MOF sensors within compact, energy-efficient devices can pick out specific molecules – even when only trace amounts are present in the air. The pores of an MOF can be designed to concentrate specific target molecules. All molecules smaller than the window to an MOF cage will get into the cage. So, we design the sensors so that the molecules we are interested in sensing will reside in the cages longer. The huge internal surface area created by these pores makes them incredibly responsive. Even just a few trapped molecules can trigger a clear signal.

These sensors also work at room temperature and our research suggests they are more precise and adaptable than many traditional chemical sensors.

Toward real-world impact

The main challenges lie in improving MOFs' long-term durability and environmental resistance. Many frameworks degrade under humidity or heat, though some research groups are looking into how to make them more stable.

When combined with machine-learning algorithms, these sensors can learn to recognize patterns from several gases at once, rather than detecting just one chemical at a time – much like how a human nose can tell different smells apart. This capability could even extend to human breath monitoring, where subtle changes in exhaled gases provide early clues to diseases such as diabetes, lung infections or cancer.

Researchers are working to embed MOFs into flexible films, printed circuits and wireless devices. With these new advances and further research, MOFs could bridge chemistry and engineering one day. As the Nobel Prize recognized, MOFs exemplify how design at the molecular scale can help mitigate problems humans face at a global scale.

If researchers can scale up this technology and overcome the challenges, networks of fiber-optic and microwave MOF sensors could one day monitor industrial plants, pipelines and even human breath for unwanted chemicals to improve safety, efficiency and health.

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