THE DEDICATION TO Beautiful Structures

INTERVIEW WITH DR. OMAR YAGHI

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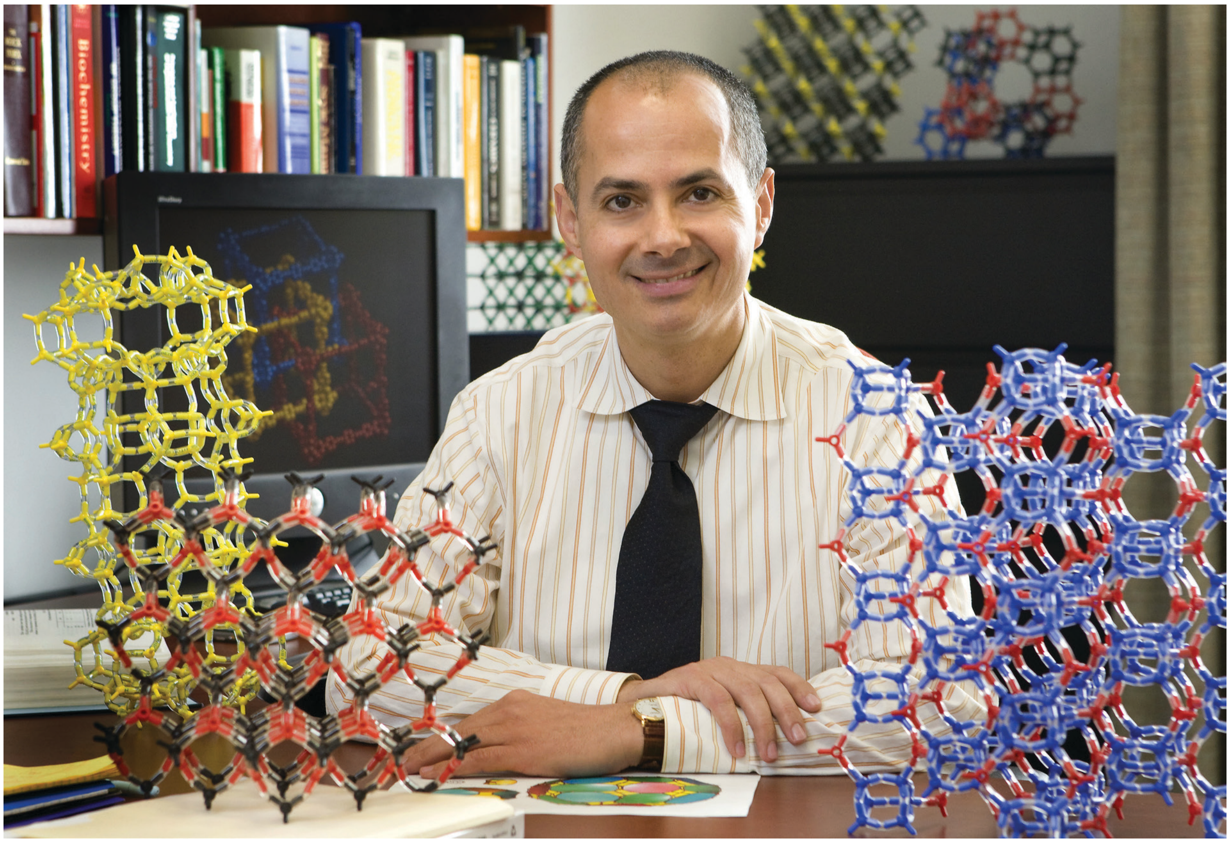

Omar M. Yaghi, *is a renowned reticular chemist who is currently the James and Neeltje Tretter Chair Professor of Chemistry at UC Berkeley and a Senior Faculty Scientist at Lawrence Berkeley National Laboratory. He also serves as the Co-Director and Chief Scientist of The Bakar Institute of Digital Materials for the Planet (BIDMaP). Dr. Yaghi conducted his Ph.D. research in Professor Walter G. Klemperer's lab at the University of Illinois Urbana-Champaign and completed his postdoctoral studies at Professor Richard H. Holm's lab at Harvard University. He is widely known for his pioneering work on metal-organic frameworks, covalent organic frameworks, and zeolitic imidazolate frameworks, which are actively used in clean energy storage and generation. His contributions to the field have been recognized with numerous awards, including the Solid-State Chemistry Award of the American Chemical Society and Exxon Co. (1998), the US Department of Energy Hydrogen Program Award (2007), the King Faisal International Prize in Science (2015), and the Wolf Prize in Chemistry (2018). In this interview, we discuss Dr. Yaghi's journey into reticular chemistry, the chemistry of creating extended crystalline structures with strongly linked molecular building blocks. We cover his recent work on harvesting water from air to address the global water crisis and delve into his efforts to create a global network of partnerships and collaborations.*

BSJ: BSJ: What first drew you to studying science?

OY: I came to the U.S. at the age of fifteen without having finished high school. I picked up the phone, called my family, and asked, "What do I do in America?" They said, "Go to the nearest college and show them the grades that you have from ninth grade." However, when I showed them my grades, they told me that they could not admit me because I did not have a high school diploma. They told me I could take classes that a freshman would take, and if I did well, they would matriculate me at the end of the term. I ended up doing okay, and I was admitted to Hudson Valley Community College. Later, it was necessary that I get a high school diploma, so I took a high school equivalency exam. In those days, a lot of older people were taking it with me, and I was the youngest one. I then transferred from that two-year college to a four-year college. I later invented reticular chemistry, but this invention was a result of my childhood experiences.

When I was a kid, about ten years old, I was not like the other kids. During the break in the middle of the day, I just sat there all by myself. One day, I wanted to see what was in the library. The library was supposed to be closed during the break, but the door was not locked. I looked inside a book, and there was a drawing of what I later learned were molecules. That drawing, which was a stick-and-ball model of a molecule, attracted me—the mystery of it was exciting. I began to learn more about molecules, and I became interested in learning about how things are made up to a level that we can see.

BSJ: Could you describe the journey that led you to studying reticular chemistry at UC Berkeley?

OY: In college, for some reason, I found myself in three different labs at the same time: one researched biophysics, the other studied physical organic chemistry, and the third centered on theory. I later saw the recommendation letter that the theory professor wrote on my behalf for graduate school. He said that I would be a brilliant theoretician, but little did he know that I was really interested in experiments. I then went on to graduate school at the University of Illinois. The reason I chose to attend graduate school there was entirely because of the beauty of the molecules that one of the professors was working on; I saw a drawing of the molecules that he was working on in a brochure and immediately decided to apply. I thought if I was admitted, I would go meet this professor, and if he was nice, I would join. He was indeed charming, so I joined—his name is Walter Klemperer. During my time in graduate school, I realized that the way we were making materials up to this point could be described as a "shake and bake"; we mixed things together and heated the result up to high temperatures to get what we wanted. However, I was attracted to the alternate possibility of taking molecules as individual building blocks and stitching them together to make different structures. At that time, though, most people saw taking a chance on this idea as a leap of faith; it was believed that when you start linking things together by strong bonds as I proposed, you would not be able to produce crystalline materials. Others had previously tried to do this and ended up with ill-defined, amorphous amorphous materials.

Arizona State University ended up taking a chance on me. In my lab, I initially had a temporary student who would take inorganic clusters and stitch them together. That worked, but the development of metal-organic frameworks (MOFs) only occurred once another student joined. Nobody was taking this student because their English was not so good. Twenty years later, when she came to visit me here, I discovered that she had been actually selling flowers on the streets of Phoenix. When I joined UC Berkeley as a new professor, before my lab was even open and equipped, she came knocking at my door saying, "I really want to work with you." I took her in, though at the time I was not interested in anything metal-organic; I needed to do something novel to get tenure, but there were hundreds of these compounds of which she was making the 110th form. She chased me around for a year and got enough done for a paper. As we were writing it, I discovered an opportunity to strengthen the bonds between metals. In this case, we took metal ions and linked them up organically because they were charged. These linkages were strengthened by both the metal coordination bond and ionic bond. This created the very kinds of materials that people said were not going to crystallize; however, we were able to do just that. She was key in making the first crystalline MOF back in 1995. That is how the beginning of reticular chemistry started. Later, I had another student who noticed that MOF structures look open and wanted to prove that they do not collapse as things pass through them—that they are not architecturally frail. The fact that the nodes are multi-metallic helped us make these architecture-robust frameworks. As metal-organics, a metal from anywhere in the periodic table could be used, and the organic could be almost anything you can imagine. The key was figuring out a way of crystallizing that is applicable to a wide range of building blocks and compositions. In 1998, we wrote a paper on their porosity, and almost no one really took notice of it until our next paper in 1999, where the porosity basically set a new world record. It was about three times more porous than the previous records set by traditional materials like zeolites. Once MOFs broke the record, everybody took notice. It was very exciting because, for the first time, chemists could assemble extended structures whose porosity can be designed and chemically modified. By controlling the pore, you could correlate your material with an application, such as hydrogen storage, carbon capture, and water harvesting.

BSJ: We have noticed the intricate structures of MOFs and covalent organic frameworks (COFs) in the posters and papers displayed in your lab; we have been told that your passion is the discovery of "pretty things." Can you tell us more about that?

OY: My whole life in chemistry has been defined by seeking out beautiful structures and making them. Back when I was an assistant professor at Arizona State and we started linking molecules together, everybody was doing nanochemistry and organometallic chemistry, and the foolish ones like me deviated from that. It was really worthwhile for me to break away from tradition. The crystals that we sought and worked very hard at producing, such as the material that I mentioned broke the porosity record, looked like diamonds. Who wouldn't fall in love? But, I knew deep down that we were addressing an intellectual challenge in chemistry on controlling matter in multiple dimensions. I am still fascinated by the beauty of nature and the beautiful things that molecules can be made to do. For example, the latest developments in our lab interlace "threads" of molecules to make a "woven fabric" of compounds. It is really a dream come true for me to create compounds that are not just beautiful, but also very useful.

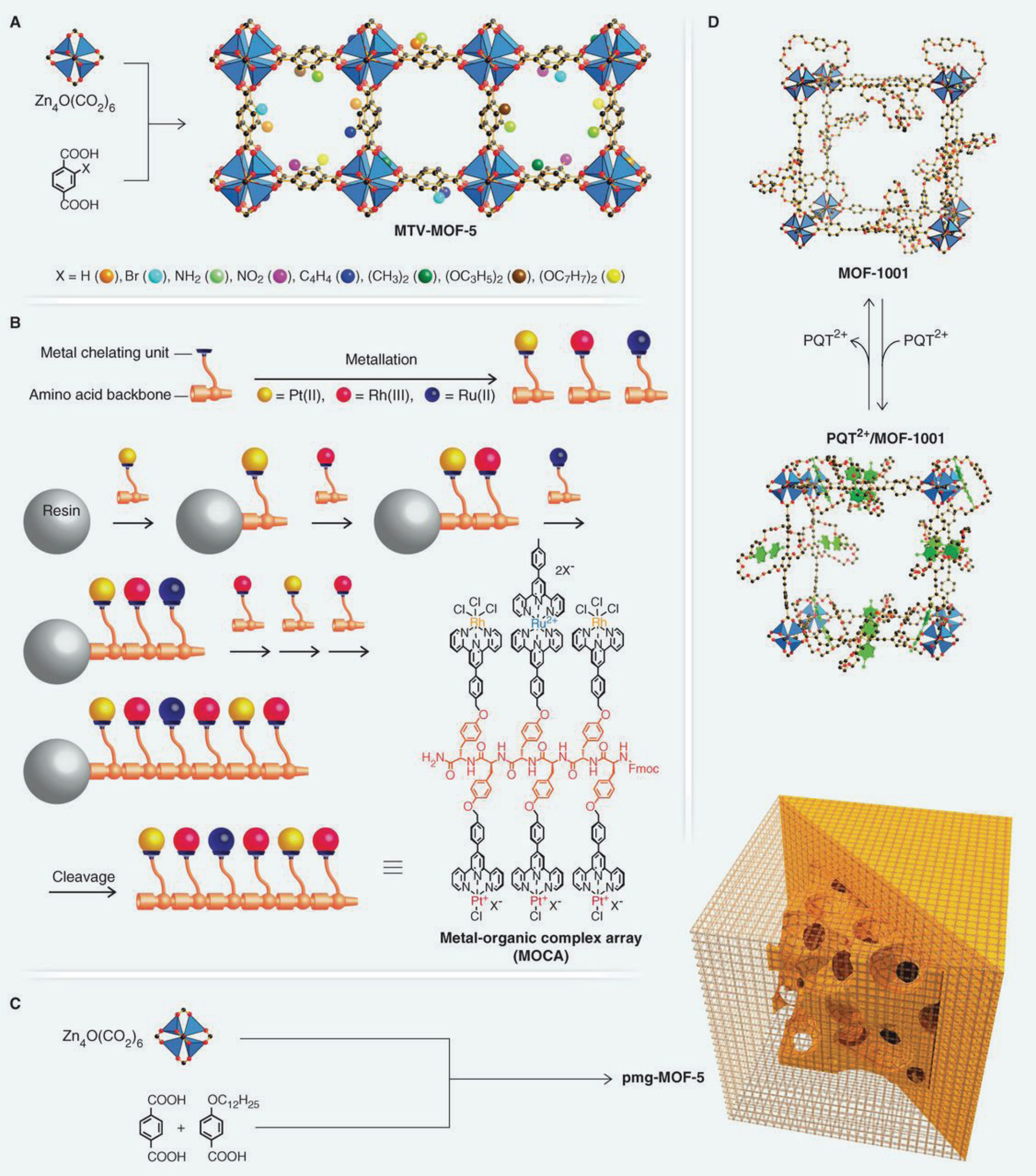

Figure 1: The Construction of MOFs. Each panel demonstrates the creation of different MOFs from their heterogenous chemical building blocks. The MOF-5 in Panels A and C is designed to bind carbon dioxide, while the MOF-1001 in Panel D binds Paraquat, an herbicide. Panel B depicts the creation of a sequence-dependent metal-organic complex array.

BSJ: In 2013, one of your publications highlighted the explosive growth of MOF creation, with over 20,000 new structures developed in a decade. What has enabled this rapid development of new MOFs?

OY: When we made MOF-5, the one that broke the record of porosity, I modeled its name after the established zeolite ZSM-5, a porous, inorganic material used in petroleum refining, because I knew it would have a similar level of importance. I think what allowed the explosive growth of MOFs is that, if you look at our papers from early on, we describe the synthesis of our compounds in such great detail that a high school student could reproduce the work. That detail has helped others enter the field. When you invent something, one option is to keep the know-how within your lab, and you become the god or king of that field. Or, you let others learn about the invention by describing the procedures in great detail so that others do not have difficulty reproducing the work.

The other aspect of the explosive growth is that as I became more and more noted for my work throughout my career, other scientists have moved into the field. I think it is important that we create an atmosphere of support for other scientists. That does not mean that we compromise the quality or the rigor of the science; rather, we need to communicate the science, the rigor of the science, and the excitement of the science, and whenever possible, allow others to thrive and become stars in their own right in the field. This field mushroomed because the chemistry works—people can actually follow the "recipes" in the original published work—but also because there was an atmosphere where people could pick their own direction as a new researcher and become a star for their own ideas. In many ways, we opened the door, but a field is not built by one person, try as they might. A field is built because many people plug in. I think that is why this field is being practiced in so many countries around the world. It is one of the most productive fields in chemistry.

BSJ: You are quoted as saying, "Humanity has never faced a problem that we could not solve when we committed resources and had the will to solve it." How does your recent work on harvesting water from air serve this cause, and what is the mechanism by which you do this?

OY: One thing about humans is that we do not do much about our problems until they are facing us and beginning to strike us down. But, I believe that we have infinite capacity to be creative and to innovate. The MOF and COF fields came out of nowhere. Chemists were going in one direction, and MOFs and COFs developed their own direction. Nobody anticipated this. What is important to keep in mind is that we, as humans, are very innovative and have a tremendous capacity for creativity. We should never forget that. I do not know of very many problems where humanity said, "We need to fix this," and someone did not come up with a creative solution. The nature of technology and advancing civilization is that with every invention, there are pros and cons. There are unintended consequences. Smart civilizations anticipate those and find solutions for them, but that requires planning. I am always optimistic. With the pandemic, I was absolutely convinced that there would be a viable solution that would save us. It actually came fairly fast because, among other aspects, we supported basic science, and people, in turn, were able to find innovative solutions. Harvesting water from air was an amazing discovery in my group because of the innovative students that had the will to make this discovery.

Having grown up in the desert, I realized that MOFs' ability to take up water at 20% relative humidity makes them suitable for use in the very low humidity conditions that many Mediterranean regions experience most of the year. The important part is that you can use MOFs to remove water from the air at 45°C, which is the daytime temperature in some desert areas. These realizations gave me the idea to harvest water using a powder—an MOF—that takes up water from air and then releases it under mild conditions. Only sunlight is needed for this process, so it is energy efficient. It turns out that, because we made these materials in crystalline form, you can use X-ray diffraction and neutron diffraction to determine where the water molecules are sitting in the MOF. The beauty of looking at the minuscule level is that nature is infinitely fascinating—it awaits our investigation. When we went into the MOF's pores, we realized that the first water molecules were making clusters, or seeds, containing five water molecules. These seeds sit in the pore and allow more water to come in and hydrogen-bond to the seeds. When you remove water from the pores, you do not remove the seeds but, instead, everything that is attached to that seed. Seeding the very first water molecules proceeds in a very cooperative way. The MOF is very hungry for water because it has hydrophilic sites: the water comes from the air, attaches itself, makes a cluster of water molecules, and becomes a seed that attracts more and more water until the pores are filled. Even though those sites are hydrophilic, because of the organic component of MOFs, the water molecules also disperse with hydrophobicity. The hydrophilic-hydrophobic grid inside the pores allows you to then take the water out at a higher temperature.

We scaled this up to kilogram quantities and tested it in the desert, where it worked. We were able to harvest clean water. This is a new resource that could be harnessed to produce drinking water. As a child, growing up in the desert climate of Amman, Jordan, my job was to get up early in the morning and open the faucets that brought water from the city so that we could store it in our reservoirs. Water only came about once every two weeks. It would come for only about six hours, starting at some ungodly hour like 6 am. I would get up and wait for it to make sure all the faucets were open when it began to flow. The water we stored in those reservoirs was all we had to use over the

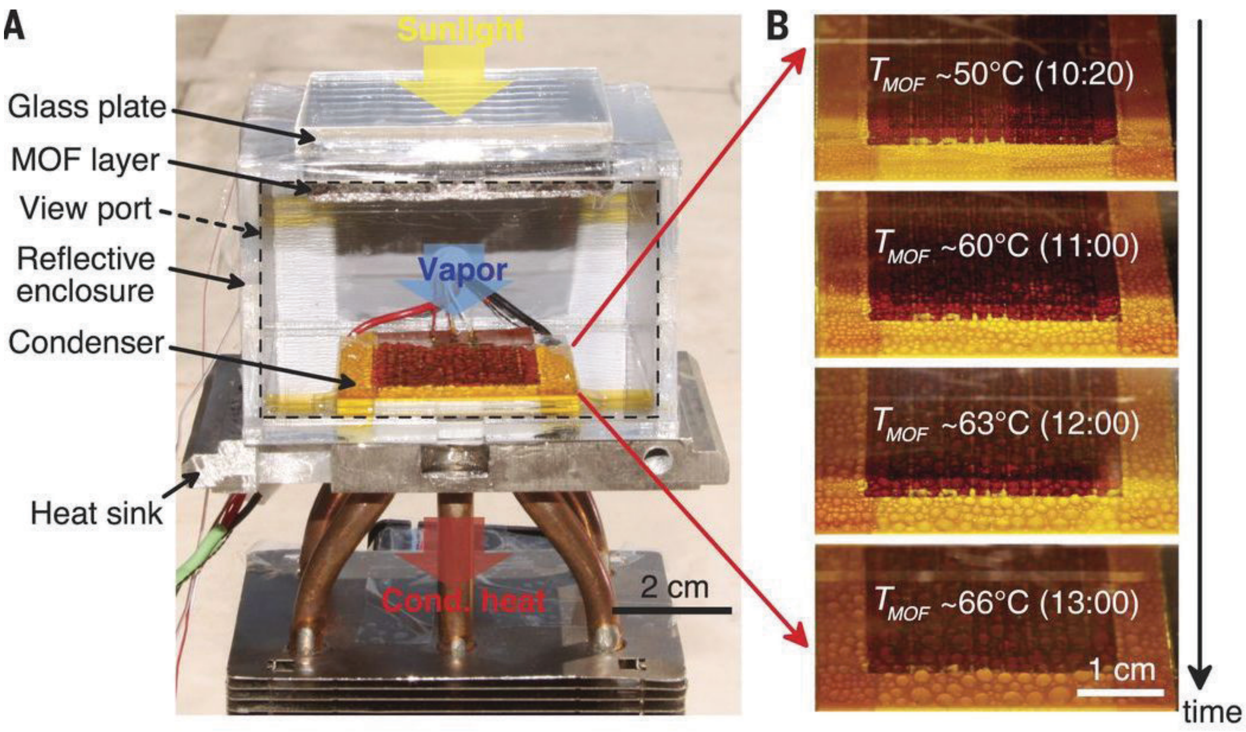

Figure 2: Prototype for Water-Harvesting Throughout Day. A prototype with a MOF-801 layer was tested overnight on an MIT roof. The right panel shows the temperature, local time, and formation of water as sunlight promotes desorption.

two-week period. If it ran out, you had to find another way to get your water, such as borrowing from someone or buying it from an expensive commercial entity. I like this connection between what happened in my childhood and what we have discovered in my lab. It speaks to the power of passion and the power of doing what excites you rather than having your whole life planned out like a blueprint. I do not think my life would have evolved to be so exciting if I had followed some blueprints. I always tell my students that they should allow themselves to work in chaos and let nature teach them something. Do unplanned things—it is okay. We are all programmed for success nowadays. We forget that nature is so rich and so amazing and that what it has to offer us perhaps is much greater than we think. When I was a kid looking at those molecules, little did I know that I would be the one that stitches those molecules together, or binds those methane molecules into pores to make natural gas tanks for automobiles. You can see that my life has been a dream come true for me. I am a very, very happy person.

BSJ: You have addressed the global water crisis and your mission to "give citizens of the world water independence." How do you plan to make your MOF technology readily accessible, and at what cost?

OY: In our lab, we have taken our work from basic science all the way to a pilot. In fact, we went to the Arizona desert, the Mojave Desert, and more recently, although not yet published, to Death Valley. We showed that these MOFs can work under the harshest conditions. The next step is to use my two startups, to which I serve as a scientific advisor, to commercialize this technology. That is a different world—the business world. It works on a different rhythm and at a different pace than academia. For now, I think that our work is progressing very well, and we are taking our prototypes to the next level. For example, one prototype employs around 200 grams of MOF and delivers about five liters of water a day. The MOF can stay in the device for the lifetime of the electronics: five to six years. It is very, very exciting.

In terms of cost, people sometimes say, "MOFs are new materials; they must be very expensive." But, in fact, you are only using 200 grams that stay in the device for five to six years. It could even be gold—which it is not—and it would be cheap. At the end of the journey, the MOF can be disassembled and reassembled in water with zero discharge. I love people who listen to my talk and say, "Well, isn't that expensive?" Then I say, "Well, how expensive is it? How much does a MOF cost?" They are not able to tell me. They do not know. They just heard something, or they assume that new materials must be expensive. That is not true. In the world of business, just like in academia, people who are really bold and believe in something will get there. I hope, at least in the startups I have, that belief is there, and we will ultimately bring this to society. At the level that I just described, a family of four could have enough water per day for $1. And we have not even commercialized it yet. That is water coming from the air. You have no questions about its cleanliness or where it came from, and you are in control of your own water. My dream is to give the citizens of the world water independence; I think we can get there. We are not going to get there tomorrow. But by "tomorrow," we can get the prototypes in the hands of people, especially those that live in water-stressed regions of the world or those who live in areas that are humidified but whose water is not very clean.

BSJ: As the Founding Director of Berkeley's Global Science Institute, you have formed partnerships across the globe, from Saudi Arabia to Argentina. Could you walk us through the process of creating such a vast global network and your motivations for doing so?

OY: MOFs have become pervasive in academia, and my name is connected to them. This started with Vietnam—I had a Vietnamese delegation coming to my office that basically said they would love to create a program on MOFs. They were interested in MOFs because of their applications and beautiful structures—and because they are exciting. I said, "Okay," and went there for a visit but discovered they did not have any labs in which we could make MOFs. This then evolved into creating an institute and equipping that institute with benches and laboratory equipment so Vietnamese scientists would be able to make new materials. We later went on to develop a model for how what I call "global science" works.

I have always been interested in bringing research to younger generations—I call them "emerging scholars." As a kid, I would have loved to be able to use my free time to play with stuff in a lab. We realized very quickly that this was providing an opportunity for young researchers to build their knowledge, learn how to do research, and even how to discover. In Vietnam, we had developed this model as an institute, and one of those students is now a postdoc in my group. In the end, not only did we realize that we were learning along the way and helping students become competitive internationally, but we were building science in that whole country—we were teaching researchers how to do research on an international scale and standard. Governments became very interested in this and started to give similar centers we set up globally a lot of funding. Every country wants to build its scientific infrastructure because they know that that leads to innovations, innovations lead to technology, technology leads to a stronger economy, and a stronger economy leads to the betterment of the standards of living. It was a real hit.

When we went to Malaysia, the model was different because we learned from our experience in Vietnam, about which I wrote a paper. We learned that when you create something new, and not everybody is a part of it, the ones that are not a part of it start throwing darts at it, trying to pull it down, even though it benefits everybody in the end. We became sensitive to how our model could be made sustainable—when we went to Malaysia, we made it virtual. We created a program that everybody could plug into, and then our mentors were around to help anybody. Every place we have set up a branch has a different model—a function of how that Institute operates—for how people work together based on the resources available at the beginning. We found great reception from the universities, as well as government funding. I hope I can have more time to really strengthen that model. From my childhood experience, I believe that every student is able to invent, able to discover, and able to change their environment. I had mentioned that a member of my lab is a product of the Institute. He is a very successful, well-known chemist and, I am sure, has transformed his family by being where he is today.

BSJ: What does it mean to you to have the opportunity to mentor graduate students just starting out in their careers?

OY: This is actually what drives people like me to get up every day. I am not saying this as a cliché. Someone like me, who has built a whole new field of chemistry at the pinnacle of my field, having received every award a chemist could receive—I do not need any more. What remains is the impact you make on others. Hopefully, we can make an impact through these applications of our work and by making chemistry more exciting to others. To students who come in and are perhaps not so prepared to do research—not so prepared to deal with failure in the lab—we tell them, "You are not failing; you are learning what does not work. These failures are increments toward success because you are learning along the way." I am a bit selfish about that. I see them as fresh minds that go into the lab, and I get up every morning rushing here because there may be a discovery that they made. In the meantime, I take mentoring very seriously with them; I care a lot. My students, if you talk to them, will tell you that I am accessible even though I am running three centers, have to travel to give talks, teach, and so on. They know that when they want to talk to me, they can come in and talk to me. I prioritize the students because they are everything. Without students, you do not have research, and whatever you do does not have much worth. Students create that freshness that pioneers need, that freshness that discovery requires. I try to make sure that they have no preconceived notions about whether an experiment is going to work or not. The motto of my lab is that if it did not work, it is because you did not make it work. That is because I think that with enough effort, you can make anything work. Nature is immensely generous with the things that it offers us. Everything can work, and we have only scratched the surface of our chemistry. Working with students is hard work. For example, when we write papers, we go through many iterations; we sit together and read the paper line by line. Otherwise, how will they learn how to state the objectives of the study, how to articulate the point of the paper, and how to make a convincing case for all their hard work? This work is rewarding.

BSJ: What advice would you give to someone who is just starting out in your field, such as any passionate young student who wants to explore science and chemistry?

OY: Give yourself a chance. Just do the experiment. We are so fortunate to have the ability to experiment. Experiments are the beginning of everything. Experiments lead to more learning, a more refined mind, better thinking, and the advancement of knowledge and discovery—a discovery that might change everything. They change the way people think. You could change the current understanding and problems of carbon capture by discovering a material that will solve it tomorrow. You will miss all these things if you plan everything. Instead, do not prejudge the experiment and say, "A + B will not give C." My belief is that it will give C, and I ask them, "Well, why do you say that? Show me scientific evidence that A + B will not give C." Usually, 50% of the evidence may exist, but it is not complete. That uncertainty is what you should capitalize on.

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