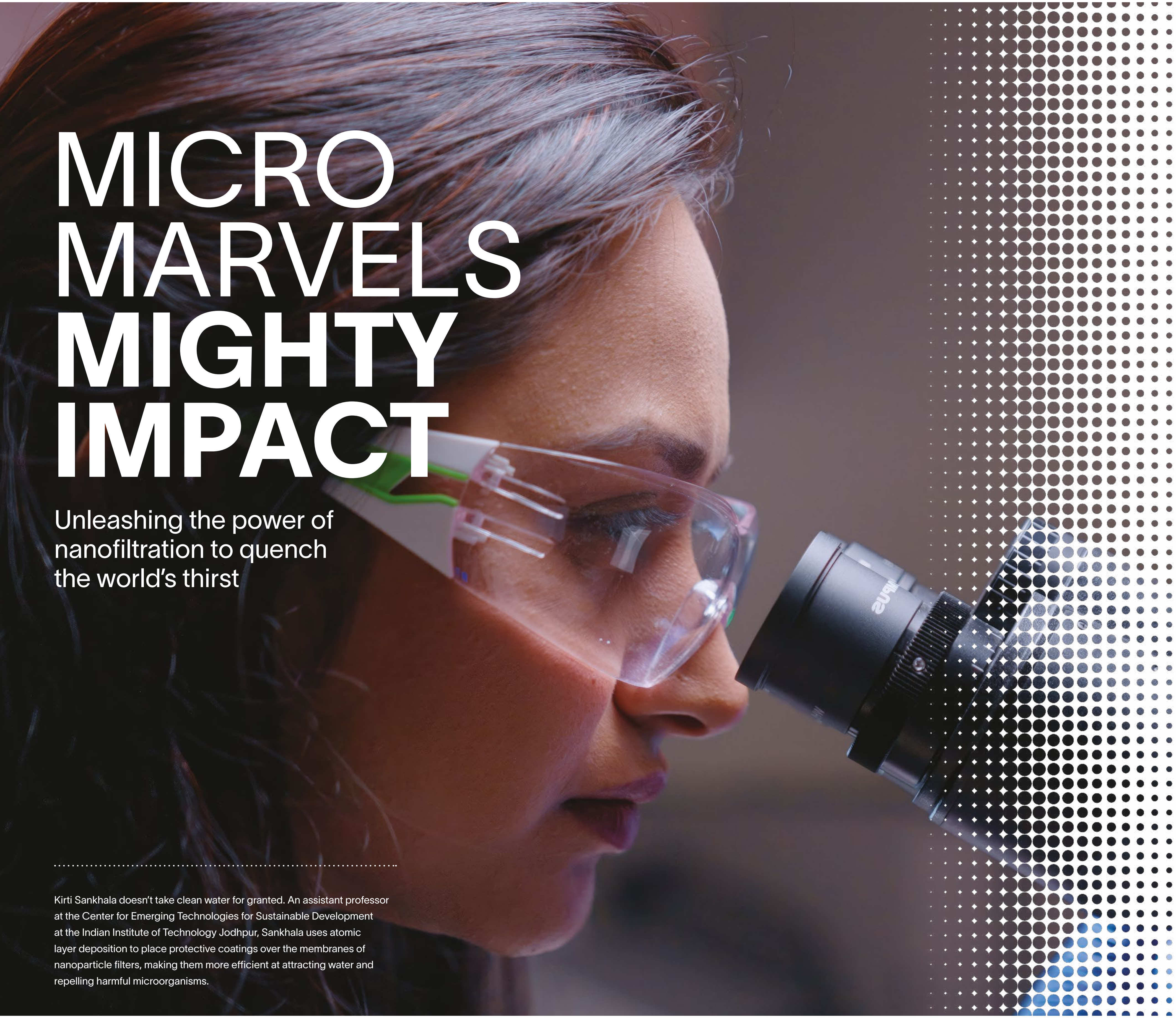

MICRO MARVELS **MIGHTY IMPACT**

Unleashing the power of nanofiltration to quench the world's thirst

Kirti Sankhala doesn't take clean water for granted. An assistant professor at the Center for Emerging Technologies for Sustainable Development at the Indian Institute of Technology Jodhpur, Sankhala uses atomic layer deposition to place protective coatings over the membranes of nanoparticle filters, making them more efficient at attracting water and repelling harmful microorganisms.

By Zac Unger
Photographs by Blue Monkeys Productions

It's easy to take water for granted. Throughout much of the world, a twist of the tap yields the instant reward of clean, abundant water, usually at minimal cost. But the process of getting that water from source to glass is staggeringly complex, involving hundreds of engineering solutions along the way.

In some places, concerns about cleanliness must be addressed because water travels through agricultural fields, small settlements or ancient pipes, picking up contaminants on its journey. In addition to disease-generating bacteria, water is often polluted with pesticides, pharmaceuticals and dyes from textile processing. The United Nations estimates that two billion people around the globe do not have access to safe drinking water and that at least half of the planet's population experiences water scarcity at least once a year. Around 17 million women give birth annually in health care facilities with inadequate water, and 206 million people spend more than half an hour per trip collecting water.

"Where I grew up, there is no 24-hour-per-day water supply," Kirti Sankhala says about her hometown, Jodhpur, in India's arid northern state of Rajasthan, where she works as an assistant professor at the Center for Emerging Technologies for Sustainable Development at the Indian Institute of Technology Jodhpur (IIT Jodhpur). "Sometimes we only get water once every two days. But water culture is different here. Everyone has a storage tank, so when water is supplied, people store it.

"We all want a safe glass of water," continues Sankhala, who was an Azrieli International Postdoctoral Fellow in the Department of Chemical Engineering at Technion–Israel Institute of Technology in 2021 and 2022. "We want high purity — the rejection of contaminants that are a health threat — and at the same time we also want high productivity, which means generating more clean water using less energy and time."

At IIT Jodhpur, her new research group is contributing toward objective number six on the United Nations' list of sustainable development goals: ensure availability and sustainable management of water and sanitation for all. For Sankhala, that means providing sustainable water treatment solutions using local natural resources, such as sand, clay and plants, as well as applying emerging membrane technology for water treatment.

Her research focuses on nanofiltration, in which water is forced through microscopic pores to filter out contaminants at a molecular level. The pores in these membranes are between one and 10 nanometres in size. (For comparison, a human hair is 100,000 nanometres across, and a bacterium is 2,000 times larger than the smallest pores in Sankhala's membranes.) Cleaning water with a membrane, then, is like making coffee in the morning, she says: "You pour everything into the filter on top and then only your coffee will come out, but all the particles will stay on top of the sieve."

Unfortunately, it's not quite that easy, otherwise contamination and water-borne diseases would be a thing of the past. The same way you can't use a single coffee filter repeatedly, these membranes can get clogged. But while a coffee filter is cheap and easily replaced, membranes must be able to last a long time in order to reliably provide safe water on a regular basis.

Nanoparticle filtration is highly affected by electrostatic charges because of how the membranes and molecules interact. A negative charge helps the surface attract unwanted pollutants, but it also makes the membrane less hydrophilic, or less able to move water freely through its pores. A more hydrophilic — or "water loving" membrane — "will suck the water easily and repel the proteins and viruses," Sankhala explains. "But when everything accumulates on the surface, the membranes become fouled and they get less efficient, and we can't get much water through."

The challenge then becomes how to make the membrane more efficient and less prone to clogging. A problem at a nano scale requires a solution that's just as small, making this a much more complicated engineering puzzle than simply brushing coffee grounds into the garbage can and shaking out the filter. Sankhala and her colleagues are using a technique known as atomic layer deposition to place a protective coating over the membrane, making it more efficient at attracting water and repelling harmful microorganisms.

"It's literally atoms upon atoms, sitting on top of the membrane," she says. Using compounds such as aluminum oxide, "we can get the thickness we need with sub-nanometre precision. This allows us to have a layer that loves water and rejects the salts."

One of Sankhala's projects at Technion was using atomic layer deposition to deposit molecules of aluminum oxide on top of the polymer membrane. The polymer itself is a macro-molecule, made up of repeated units of smaller molecules, linked together almost like blocks of Lego. "As part of her work, she investigated what happens to the performance of these membranes once we grow aluminum oxide on them," says Tamar Segal-Peretz, Sankhala's supervisor at the time and group leader in the university's Functional Nanostructures and Advanced Imaging Lab (and an Azrieli Early Career Faculty Fellow from 2016 to 2020). "Along the way she discovered a very interesting thing."

The team's original hypothesis was that the aluminum oxide would grow on top of the polymers and modify the membrane on a surface level. "But in fact, what we saw," Segal-Peretz continues, "was that some of the molecules penetrated into the separating layer of these membranes," because of the way they diffuse and react inside the polymer.

Building on this finding, Sankhala is exploring the potential of atomic layer deposition for other applications. She worked on a separate project to grow inorganic material not just on top of membranes, but to make the technology work in three dimensions inside polymer foams, including those used as absorbents and insulation. (Because they have a highly porous bicontinuous structure, these foams provide a large surface area that's well suited for hosting reactions, such as the degradation of pollutants through catalytic activity.)

Foams present a complex, multi-parameter problem, however, since a combination of substances with different chemical properties is required to polymerize the foam while simultaneously maintaining a high surface area. Initially, Sankhala had hypothesized that the process would create extremely small clusters of zinc-oxide molecules, growing atop each other a single layer at a time. Instead, she found that even with a single treatment, it wasn't clusters that formed but nanorods, a more organized structure for collections of extremely small particles. Using a process called sequential infiltration synthesis — similar to atomic layer deposition except that it relies on chemical reactions that occur within the pores of a material rather than on the surface — the team was able to distribute zinc oxide very uniformly throughout the foam in a controlled way. Thanks to the catalytic activity this supports within the foam, the material is a candidate for the efficient treatment of wastewater from textile production because of the way zinc oxide nanoparticles react with dye molecules.

"This was a very impressive result," Sankhala recalls, because it allowed the team to essentially create a hyper-efficient water-treatment sponge. "Now if I have a one-centimetre cube I can treat almost one litre of wastewater from a textile plant."

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In the process of improving membranes and filtering technology, some of the most elegant work that Sankhala did was in using transmission electron microscopy to better understand the filtration process at a basic level, exploring the composition of the membranes on a nanoscale. Incorporating aluminum oxides into the polymers provided a high contrast for the electron beam, allowing her to clearly image exactly how and where the polymers were mixing with the membranes. Seeing how each experimental modification affects the membrane at an atomic resolution enhances the ability to minimize production and maintenance costs of a filter while also maintaining high performance.

The ultimate goal is to provide higher quality water treatment in the cheapest, greenest and most space-efficient manner possible. Currently, much of the world uses reverse osmosis (RO) rather than nanofiltration to treat its water. This is in part because RO, which removes contaminants by using pressure to force water molecules through a semipermeable membrane, can filter out much smaller particles than nanofiltration. It's particularly effective for purifying seawater, as is common in Israel, where more than 70 per cent of the country's freshwater comes originally from the ocean (and where 80 per cent of wastewater is treated and returned to agriculture). But the ability to hyper-filter has its downsides, as RO removes many minerals that compounds like calcium and magnesium need to be added back in for human health. More important, RO requires much higher energy input because pressure is applied to the water in order to accomplish treatment. While RO requires about 25 bars of pressure — or 25 times atmospheric weight at sea level — nanofiltration works at only four or five bars.

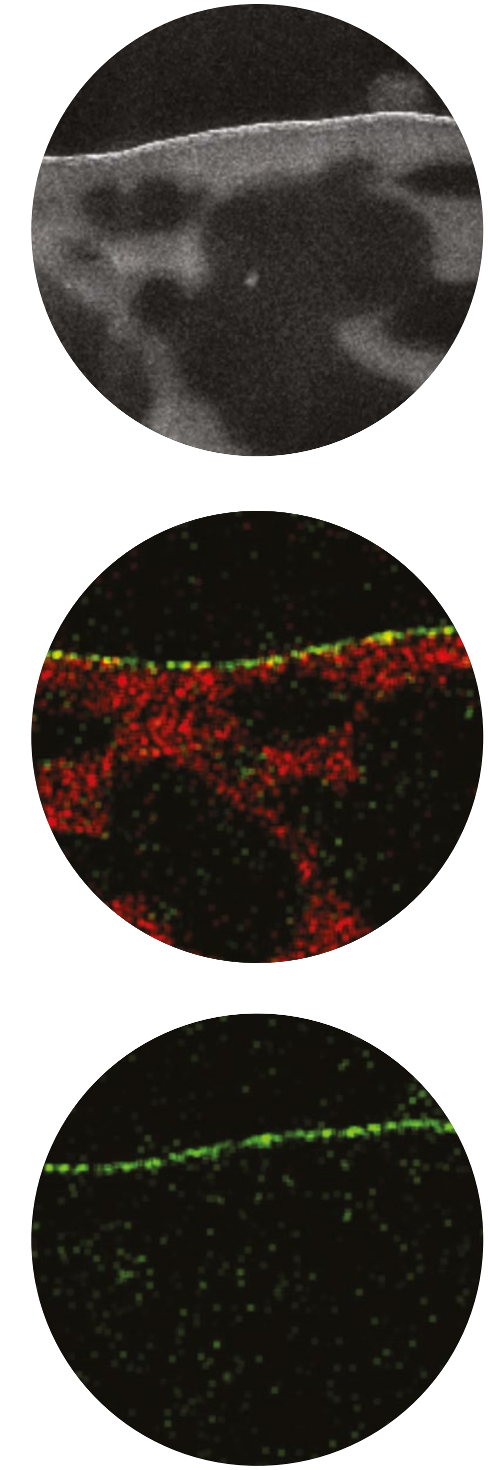
"Increasing the pressure increases the energy input required," says Sankhala. When it comes to wastewater, traditional treatment facilities are huge, energy-intensive spaces. "But if you are working with efficient membranes, you can stack them vertically and do the work of an entire plant in a single room."

Conducting research in Israel was something of a revelation for Sankhala, as she noticed that "the young generation there has crossed those thoughts of scarcity out of their mind because water is so dependable and clean." Working with the Azrieli Fellows Program was another highlight of her time at Technion. "The efforts they put in for us are so impressive," she says. "It's not only about the funding — the bond between Azrieli members is so strong, and you know that everyone is really there to support you."

Growing up in a parched region of India, Sankhala encountered water issues at an early age and was confronted constantly with concerns about both purity and scarcity. "She has both lived experience and many skills in the lab, and that combination will be incredibly valuable for her career," says Segal-Peretz. "The chance to bring life-improving reliability back to her hometown is a force that continues to motivate every aspect of her work."

While nanofiltration is already highly efficient, Sankhala is working to continue advances in this field, pushing for higher purity and lower energy costs while reducing harmful chemical by-products. Back home in India, she is supplementing her high-tech lab work with a project to help rural residents filter water through ceramic filters in earthen pots.

"The drive to have good water is a human survival instinct," says Sankhala. "It's also a human right and we have to protect the value of each drop." ▲●■



Microscopy images from Sankhala's lab work provide a close-up view of the six-nanometre-thick layer of tin oxide deposited on the surface of a nanofiltration membrane. Her team originally hypothesized that adding oxides would modify the membrane on a surface level, but in fact some of the oxide molecules penetrated into the separating layer of these membranes, providing opportunities for additional approaches to filtration.