DISCOVERY REPORT

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The future of clean water

Now on tap: Materials and strategies to save our supply

Published by
c&en

$39.99

The future of clean water

If I had to make a list of Earth's most important molecules, water would certainly top it. It's essential for life as we know it. Since 2015, when United Nations member states pledged to make safe water accessible to all by 2030, the world has made progress in cleaning its water supply.

But it's not nearly enough. Climate change is reshaping water access by causing both droughts and floods. At least 2 billion of the planet's 8 billion people use drinking water contaminated with feces, according to the World Health Organization. Even in the US, which has extensive water infrastructure, authorities have not always provided clean water to communities. A combination of old pipes and improper water treatment exposed people living in the majority-Black community of Flint, Michigan, to drinking water containing elevated lead levels. People living downstream of a Chemours plant in North Carolina found their water tainted with chemicals used in its GenX process for making fluoropolymers. The chemicals are among the per- and polyfluoroalkyl substances (PFAS) that slip through traditional means of cleanup.

This report delves into the technologies that start-ups and laboratories are developing to purify water. You'll hear about entrepreneurs breaking down PFAS with supercritical water, a company that draws purification inspiration from a cow's multichambered stomach, and firms desalinating water using innovative materials instead of fossil fuel energy.

Contributing editor Carmen Drahl, who has covered organic chemistry and green chemistry for C&EN, edited this report. It includes a reading list of papers and patents curated by our sources, as well as by information scientists at the CAS division of the American Chemical Society.

As an ACS member, you get exclusive access to the Discovery Report, a quarterly publication bringing you cutting-edge research defining the chemical sciences and our industry. Look for the next one in the first quarter of 2023.

Bibiana Campos Seijo
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INSIDE

CHEAT SHEET
5 questions and answers about clean water
P. 3

FROM THE FRONT LINES
8 experts identify challenges and opportunities for clean water
P. 4–6

BY THE NUMBERS
Discover trends in water purification
P. 7

ANALYSIS
A thirst for innovation: Local solutions keep scarce water flowing
P. 8–9

COMPANIES TO WATCH
We choose 20 promising firms cleaning up water
P. 10–12

MOVERS AND SHAKERS
Jessica Ray: Materials for real-world water treatment
P. 13

HOT SHEET
Simple chemical method destroys 2 classes of PFAS
P. 14

HOT SHEET
Superefficient solar desalination
P. 16–17

HOT SHEET
Chemistry in Pictures: MOF emulsion
P. 18

READING LIST
Our picks of the patent and journal literature on clean water
P. 19

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ACS Chemistry for Life®

CHEAT SHEET

5 questions and answers about clean water

Q. What's the state of clean water?

» **One-quarter of the world's population lacks on-site access to safe water.** Microbial and fecal contaminants transmit disease and cause nearly 500,000 deaths annually.

» **Chemicals are contaminating water, too.** Emerging pollutants include pharmaceuticals and per- and polyfluoroalkyl substances (PFAS). A body of scientific studies reveals possible links between human exposure to certain biologically active PFAS and adverse health effects.

» **Climate change and population growth are making things worse.** In arid areas, people may be displaced by water scarcity. Elsewhere, torrential floods may wash fertilizer and other chemicals into bodies of water. Fast-growing urban areas and sprawl strain water treatment systems.

Q. What are some conventional purification strategies?

» **Water purification does not need to be fancy.** Simple filters can remove large particulates like dirt. The sun's heat and ultraviolet rays kill pathogens in water, as do boiling and chlorine drops or tablets.

» **Treatment plants provide clean water to billions.** Typical purification starts by separating solids from water. Filtration steps pass water through sand, gravel, and charcoal. Many filtration systems involve pushing water through membranes with very small pores, a process called reverse osmosis. Disinfection occurs with UV light or chlorination.

» **Arid areas rely on making salty water fresh.** About 20,000 desalination plants provide water for human consumption or irrigation.

Q. What are the drawbacks of those methods?

» **Many chemicals are not removed by conventional purification methods.** Polybrominated diphenyl ethers and PFAS persist in the environment. Established filtration techniques were not designed to remove them.

» **Desalination requires a great deal of energy.** This makes desalinated water expensive (see page 8). And when the energy comes from fossil fuels, it contributes to climate change.

Q. How is chemistry innovating in the water arena?

» **New technologies are designed to rid water of emerging contaminants.** Companies are developing filtration methods that snag PFAS (see page 11), as well as coming up with ways to destroy organic molecule contaminants with plasma, super-critical water, or photocatalysts.

» **Solar-powered strategies may be more sustainable on a drier planet.** Scientists are piloting methods to pull water from air and to desalinate water (see page 8) using power from photovoltaic cells.

» **Next-generation membranes aim to streamline purification.** Coatings, bioinspired strategies, and alternative polymers can reduce clogging of membrane pores by organic matter and lengthen membranes' useful life.

Q. What's next for clean water?

» **Regulations for PFAS are evolving.** In June, the US Environmental Protection Agency announced that utilities should inform customers when the concentrations of two of the most common PFAS found in drinking water exceed fractions of one part per trillion. Drinking-water suppliers are not yet obligated to meet that limit.

» **United Nations member countries pledged to provide universal access to safe water by 2030.** They are making progress but are behind on meeting that target.

8 experts identify challenges and opportunities for clean water

Sofia Babanova

» **Cofounder and CTO, Aquacycl**

Sofia Babanova believes her company's success comes from taking the middle ground. Aquacycl's microbial fuel cells use bacteria to generate electricity while cleaning wastewater. Competitors have tried to make reactors big, which reduces performance because more electrical energy dissipates as the distance between electrodes increases. Babanova's firm instead connects together shoebox-sized reactors.

Bacteria at the device anode break down organic matter, producing dissolved carbon dioxide, electrons, and protons. The electrons create electricity in an external circuit and combine with protons and oxygen at the cathode to form water. Aquacycl's system needs 97% less energy than conventional wastewater treatment plants, Babanova says. In addition, she says, "we don't generate any methane, and we generate 90% less biomass."

A 12 m shipping container packed with 640 reactors can treat over 37,000 L of wastewater a day, Babanova says. It can handle water with organic matter concentration 100 times as high as that typically found in sewers. Such levels typically occur in food and beverage processing.

Aquacycl has three large installations and seven smaller pilot ones at food and beverage facilities. Tests have shown that the technology also works for petrochemical wastewater, which contains a complex mixture of long-chain hydrocarbons and other organic compounds and so is more challenging to process than food and beverage wastewater. The company now plans to build systems for pharmaceutical and petrochemical companies.

But Babanova says the start-up's ultimate mission is to provide at least partly self-powered water treatment systems for developing countries. For that, it is trying to find effective ways to recover the electricity produced by the fuel cells and bring down the cost of each reactor from $250 to $100 in the next 5 years. "The future of water is recycling and reuse," she says. "That's what nature does. I don't think we have a choice."

> "The future of water is recycling and reuse."

Alan Chan

» **Global vice president and general manager, DuPont Water Solutions**

Treating industrial discharge is one of the biggest challenges the world faces, Alan Chan says. But he also sees it as an opportunity to combine innovations in helpful ways. Over the past few decades, DuPont has developed and acquired technologies to cultivate a broad water purification portfolio. That allows Chan and his colleagues to develop multitechnology solutions to thorny wastewater challenges.

Factory effluent, for example, contains a complex mix of impurities at high concentrations. DuPont's product line combines four technologies—ultrafiltration, nanofiltration, reverse osmosis, and ion exchange, each of which removes different types and sizes of contaminants—to recover up to 95% of discharged water. At a textile plant in southern India, for instance, this minimum liquid discharge system removed salts, dyes, and other chemicals, allowing the facility to reuse its wastewater. The plant saved enough money in 6 months to recoup the cost of DuPont's products because the technology reduced freshwater needs and prevented pollutant discharge fines.

To address future water challenges, DuPont continues to innovate in polymeric membranes and ion exchange resins, Chan says. The company is also developing software solutions for easier automation and monitoring of its multicomponent water purification systems.

Pratiksha Dongare

» **Professor, Rice University, and director of technologies, Localized Water Solutions**

Growing up in India, Pratiksha Dongare experi-

CREDIT: COURTESY OF INSTITUTIONS

enced water and power shortages firsthand. She now develops technologies to desalinate salty and brackish water using solar energy. “Less than 1% of water on Earth is freshwater” that people can access easily, she says, and desalination is one way to address water scarcity (see page 16).

Dongare first studied membranes coated with nanoparticles that heat up when they absorb sunlight. Some salty water in contact with the membrane vaporizes, and the pure water vapors go through the membrane for condensation and collection while the rest of the salty water is held back. But membranes are fragile and clog easily from biological growth, a phenomenon known as biofouling.

So Dongare developed a membrane-free solar desalination system. Austin start-up Localized Water Solutions is now commercializing both of the technologies. The membrane-free design, a semifinalist for the US Department of Energy Solar Desalination Prize, involves flowing saline water and the distilled, collected water across two sides of a heat exchanger, which captures heat generated during vaporization to warm up the saline water. Matching the speed of the two water streams creates a circular heat flow in the system that boosts its energy, giving six times as much clean water as would result if the water flow rate were not matched. This energy amplification also stores solar energy in the system, Dongare says, “so it allows operation even after sunset.”

Dongare and the start-up team are now building a prototype, aiming to build a 100,000 L per day desalination plant, she says. “We should have real-world test data within 6 months.”

Rodney Priestley

» Vice-dean of innovation, Princeton University, and cofounder, AquaPao

Rodney Priestley cofounded AquaPao because the materials he studies seem ideal to him for addressing the grand challenge of clean water access. AquaPao’s water purification technology hinges on a spongelike hydrogel that absorbs or releases water.

Priestley’s dynamic, light-responsive polymer absorbs water at room temperature, leaving contaminants behind. It can then expel potable water when heated by sunlight. The system could purify water if electrical power is unavailable, such as in remote locations or during emergencies. “What makes our technology unique is that you don’t require evaporation, which takes a lot of energy,” Priestley says.

Raw materials for the hydrogel are easily available, and preliminary estimates suggest that a 1 m^2 membrane would cost under $100. Early tests show that the material can be reused 10 times, but the AquaPao team is evaluating possible breakdown mechanisms and strategies to extend that lifetime.

The material has shown promise for removing dangerous per- and polyfluoroalkyl substances (PFAS), known as forever chemicals. With funding from the State of New Jersey and a US National Science Foundation Small Business Innovation Research grant, the company is building prototypes and evaluating the hydrogel’s suitability for personal, household, and municipal use.

> “We’ve gotten some interesting materials that work quite well for various targets.”

Wendy Lee Queen

» Professor, Swiss Federal Institute of Technology, Lausanne (EPFL)

In Wendy Lee Queen’s view, metal-organic frameworks are ideal materials for taking on the clean water challenge. The cage-like molecules have well-defined pore sizes and distributions. Their inner surfaces are chemically tunable. Together, these characteristics enable chemists to design materials that trap specific targets. “The really cool thing about MOFs is their walls are atoms thick,” Queen says. “You can access all of the inside and outside” so that very little material can purify a lot of water, she adds.

Her group attaches polymers inside MOFs to make composites that can selectively remove heavy metals from water. Redox active polymers, for instance, are good for trapping mercury and lead, both of which bind to the polymers by accepting electrons from them. “We’re still designing materials in the lab,” Queen says. “We’ve gotten some interesting materials that work quite well for various targets.”

The team is also testing the composites’ selectivity and performance with natural water sources contaminated with ions, like sodium, that compete with the targeted heavy metals, and organic materials that can block MOF pores. In the lab, the researchers test performance at low-contaminant concentrations that are relevant to the real world, she says.

Currently, metal adsorbents remove arsenic from a cubic meter of water at a cost ranging from a few cents to a few dollars, which is lower than that possible with MOFs. Queen expects the cost of MOFs to come down with larger-scale production. For now, she is focusing on effective ways to regenerate the tiny polymer-filled cages and on finding niche uses where other materials don’t perform well.

Isha Ray

» Professor, University of California, Berkeley

Isha Ray prefers the term "approaches" over "technologies" when talking about water purification. Any clean water system "is a chain, from source to sip," says the economist turned social scientist. "Technologies don't really make sense without a cultural and socioeconomic context." They are one piece of the chain," she says, and "the entire chain matters for a clean water approach to be successful."

If a solution is to work for poor communities and nations, Ray says, affordability and ease need to be front and center. For instance, methods like evaporation systems, filters, and chlorine tablets require people to take some action to purify their water. This typically burdens women and girls and can be unaffordable for very low-income households. "Affordability is about cost relative to a budget," she says. "Households that are really short of money are almost always really short on time."

Consequently, passive approaches that can be built into community-wide systems and do not rely on individuals might sometimes make more sense. For example, researchers at the Swiss Federal Institute of Aquatic Science and Technology have installed chlorination devices at water tanks that feed community taps in rural Nepal. Ray has worked with the team to evaluate the devices' effectiveness in reducing bacterial contamination, as well as user acceptance and maintenance costs. Solutions like tank chlorination might not be perfect yet, she says, "but they're on the path."

"The entire chain matters for a clean water approach to be successful."

Stephen Rosansky

» Senior engineer, Battelle Memorial Institute

They are called forever chemicals, but Stephen Rosansky's team at Battelle has found a way to destroy PFAS that leach into groundwater from landfills and military sites. The technology breaks down PFAS into carbon dioxide, hydrofluoric acid, and water.

PFAS are an evolving group of thousands of compounds with ultra-strong carbon-fluorine bonds that don't degrade in the environment (see page 14). The Battelle team breaks these bonds by subjecting PFAS in water to an oxidant at a temperature and pressure at which there is no distinction between vapor and liquid. More than 3 years of bench-scale tests show that Battelle's supercritical water oxidation technique "can effectively destroy all PFAS"—over 99% of tested compounds—Rosansky says. Unlike other PFAS-eliminating technologies, he adds, Battelle's "will also destroy other contaminants."

A mobile system that can treat up to 1,900 L per day of highly contaminated PFAS waste should be ready by the end of this year. Battelle has contracts with the Department of Defense to treat contaminated military sites with the system. Rosansky says it will be more difficult to clean up tens of thousands of liters of waste- or groundwater from sources where PFAS are present but at lower concentrations. It is more economical to heat and pressurize smaller volumes of water with high PFAS content, so the organization plans to first concentrate PFAS with adsorbents or with other techniques.

Yang Si

» Professor, Donghua University

Millions of people die every year from diseases transmitted by waterborne microbes. Yang Si hopes that his energy-saving disinfection technology can help save some lives. Today's filters or chemical disinfectants are effective, but Si says that "the major problems with them are short service life and high cost," which makes them impractical for low-income nations.

Si and his colleagues are making robust materials that can decontaminate large amounts of water using little energy. Their strategy is to embed bactericidal materials into aerogels made of hydrophilic silica nanofibers. Water flows through the porous spongy gels quickly, and the 3D network enhances bacterial contact with the biocide. The water flow sweeps the dead bacteria out, keeping the material from fouling.

The researchers have in the past coated the nanofibers with chemical groups that kill bacteria. Their latest approach is to embed conductive silver nanowires in the gel's network of nanofibers. Sending electricity through the wires kills bacteria and viruses by rupturing their cell walls.

Si says the nanowire-embedded aerogel costs twice as much as commercial filtration membranes, but the aerogels make up for it by being less prone to biofouling and having higher filtration capacity. He says a 1 m^2 membrane should be able to handle over 2,000 L per hour—at least four times as much water as a commercial membrane, while consuming a hundredth of the energy, or less. These features, plus its strength, make the material good for use in homes, "especially for rural communities," he says.

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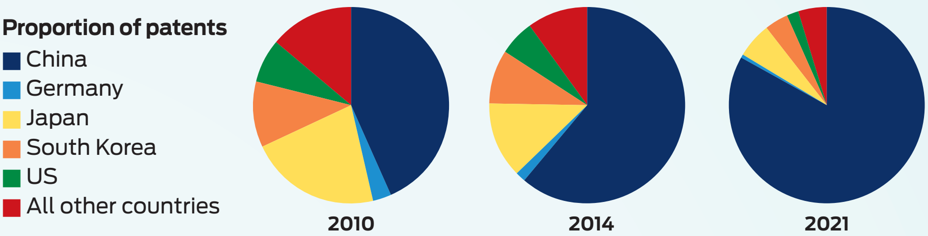
Discover trends in water purification

Where in the world

China has an increasingly large lead over all other countries in patents related to clean water.



Who's doing what

We found the companies and institutions most active in filing patents that mention clean water in three strategies of interest.

Biological wastewater treatment		Adsorptive wastewater treatment		Wastewater treatment, flocculation	
Assignee	Number of Patents	Assignee	Number of Patents	Assignee	Number of Patents
Kurita Water Industries	89	Changzhou University	101	Sinopec	60
Beijing University of Technology	73	Nanjing University	69	Kurita Water Industries	47
Sinopec	71	Sinopec	54	Sichuan Normal University	33
Organo Corporation	47	Tongji University	44	Changzhou University	21

Patenting leaders

We found the company most active in filing patents that mention clean water in each of the top five countries. Although some of these companies specialize in water purification, others do not.

Assignee Country	Top Assignee	Number of Patents
China	Sinopec	1,183
Japan	Kurita Water Industries	1,126
South Korea	Coway	326
US	General Electric	250
Germany	Siemens	90

Clean water stats

Boost your knowledge with our selection of facts and figures.

1 in 4

People worldwide who lacked access to safe drinking water in 2020

485,000

Estimated number of deaths worldwide annually from diarrheal diseases due to water contaminated with pathogens

>12,000

Number of per- and polyfluoroalkyl substances (PFAS) included in the US Environmental Protection Agency's master list of PFAS

1999

Year the US Centers for Disease Control and Prevention began measuring PFAS levels in people's blood serum

130 billion

Liters of wastewater processed daily by public water treatment plants in the US

13.8 million

Metric tons of sludge—residual semisolid material—produced annually by public water treatment plants in the US

Sources: CAS Content Collection, *J. Environ. Manage.*, UNICEF, US Centers for Disease Control and Prevention, US Environmental Protection Agency, World Bank, World Health Organization.

Notes: CAS information scientists searched patents and publications containing the concept of clean water from 2010 to 2021. "Publications" include journal publications and exclude conference reports, books, dissertations, reports, and preprints. Patents may mention more than one type of technology. Patent records lacking data on assignees or assignee countries have been excluded from this analysis. Figures for Germany may include patents published after a long delay that were filed in the former East Germany.

ANALYSIS

A thirst for innovation

ALEXANDRA A. TAYLOR, C&EN STAFF

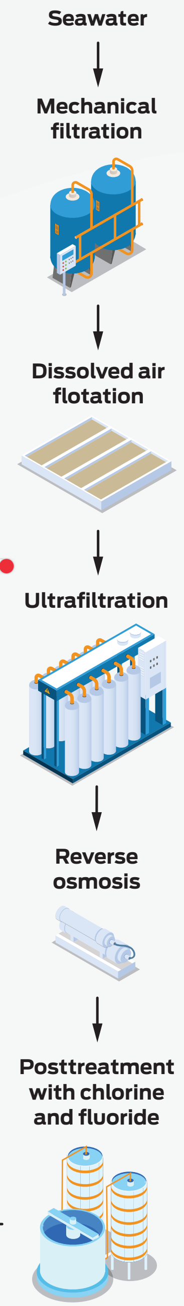
In late 2017, after years of declining dam levels and scarce rain, the city of Cape Town, South Africa, was in a severe water crisis. The government warned of Day Zero, when water levels would be so low it would have to cut off household access. In anticipation, it diverted water from agriculture and limited residents to 50 L of precious liquid per day. Residents did their part by recycling laundry water, taking fewer showers, and using hand sanitizer rather than washing with soap and water. The campaign worked: by June 2018, the drought had eased enough for officials to call off the emergency. In the meantime, residents had become much more efficient with their water use, and the city had adopted effective water-saving strategies, such as reducing water pressure.

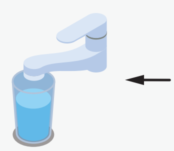
The specter of a Day Zero still looms for Cape Town and for many places around the planet. In part because of climate change, water scarcity could displace up to 700 million people by 2030, according to the United Nations. And worldwide, people are most likely to experience climate change through its effect on water. As water availability in drier areas decreases, industrial, agricultural, and municipal interests will compete for water of increasingly low quality. Water purification can be costly, so chemists and engineers are working to make less expensive, more energy-efficient technologies that will be more widely accessible. “Just getting access to water itself of any quality is becoming a challenge in dry regions,” says David Dzombak, head of Carnegie Mellon University’s Department of Civil and Environmental Engineering. Here are some solutions that will help slake the thirst of a drier planet.

Desalination

Desalination plants are already common in coastal areas such as the Arabian Gulf and are becoming more attractive in places like inland Texas, where the groundwater is brackish. But the plants cost hundreds of millions of dollars to construct. The water they produce is expensive, costing between $1.30 and $2.60 per 1,000 L depending on the price of energy.

In 2018, Singapore opened the $153 million Tuas Desalination Plant. Tuas pretreats seawater using dissolved air and semipermeable membranes, which extend the lives of its reverse osmosis membranes. It uses about 3.5 kW h to produce 1,000 L of clean water, and the roof is partially covered in solar cells to offset a small portion of its energy needs. In 2020, Singapore residents paid a hefty $2.74 per 1,000 L for a mix of local, reclaimed, imported, and desalinated water. Today, Singapore has five desalination plants, of which Tuas was the third to open.





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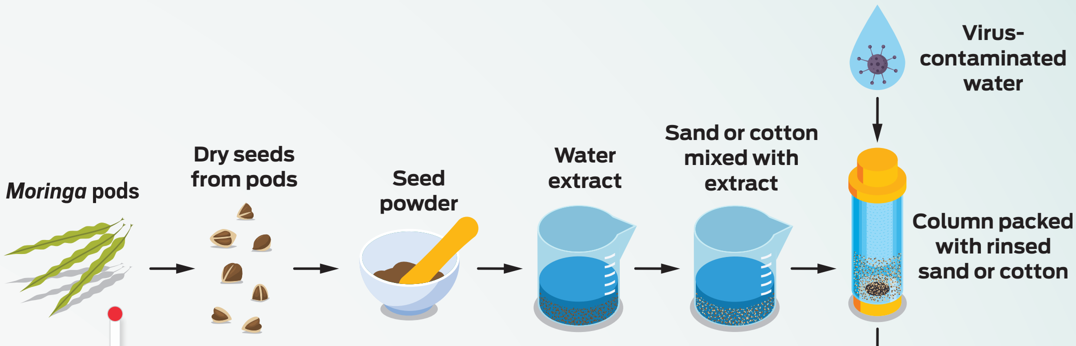
Direct potable reuse

Perhaps the best way to increase water supplies is to reuse the water we have. With intensive treatment, wastewater can be returned to taps without first being released into the environment. In the US, only a single such plant has been built, in Big Spring, Texas. But the method is gaining traction in other states facing water scarcity, such as California.

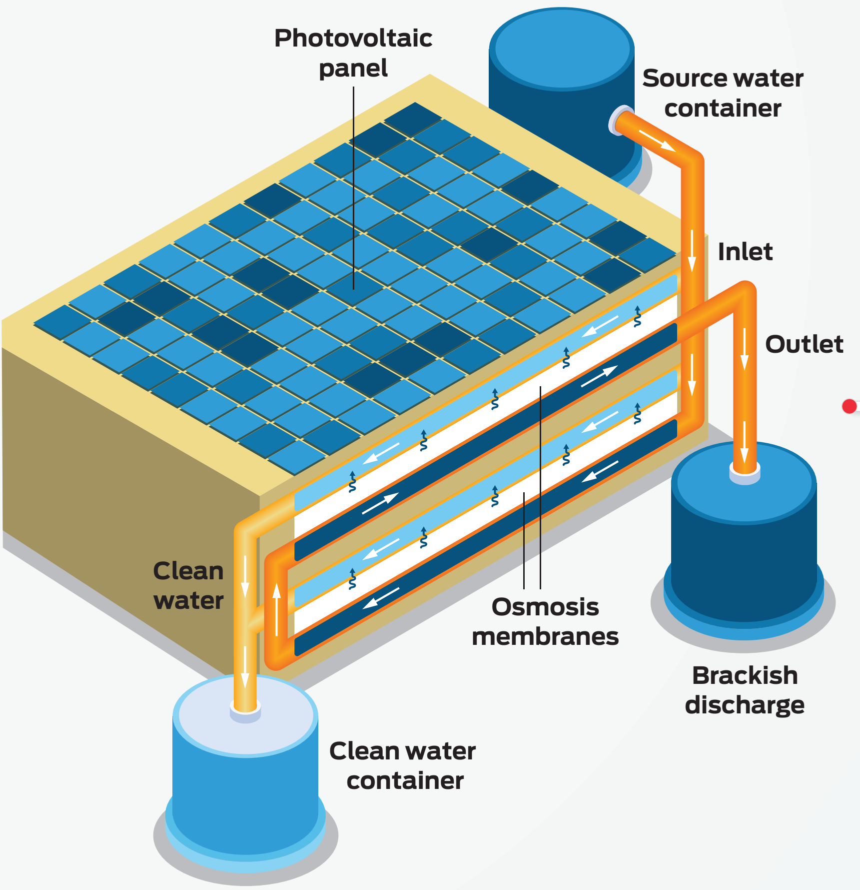
El Paso Water successfully completed a wastewater treatment pilot program in 2016. In September, the utility announced $20 million in funding to build a facility to transform treated wastewater into safe drinking water. The funds come from the Bureau of Reclamation, part of the US Department of the Interior. Construction is slated to start in late 2023, and the facility is expected to produce up to 10 million gallons a day. The utility estimates water from the plant will cost $1.06 per 1,000 L, after factoring in the cost of construction and operation over a 20-year period.



Filtration

In resource-poor regions, the first priority is to remove infectious disease agents from the water. Locally made filters built from abundant materials can remove pathogens such as *Rotavirus*.

Manish Kumar of the University of Texas at Austin, Stephanie B. Velegol of the Pennsylvania State University, and colleagues have developed a prototype filter that relies on extracts from the seeds of *Moringa* plants, which are found in tropical and subtropical regions of South Asia (*Environ. Sci. Technol.* 2019, DOI: 10.1021/acs.est.9b03734). These areas are also hot spots for waterborne illness. A filter made by mixing sand or cotton with the extract strips bacteria and viruses from the water. The filter is intended for residential or community use. It costs less than $2 per person per year and requires no power: the filter relies on gravity to pull the water through.



Solar-powered purification

In remote regions of Africa, the Middle East, and Australia, where sun is abundant but clean water and energy are at a premium, modular photovoltaic purification units can supply small communities with drinking water. These systems use solar power to purify contaminated rain, brackish groundwater, or seawater.

Efforts in this area abound. A team from the Massachusetts Institute of Technology led by Steven Dubowsky has successfully implemented a solar-powered reverse osmosis unit to supply clean drinking water to the Mexican village of La Mancalona. The unit is designed to meet the needs of a few hundred people at a fraction of the cost of bottled water. In 2019, a team from King Abdullah University of Science and Technology reported a method for harnessing the waste heat typically generated by solar cells to distill drinking water by evaporating it through a membrane. Brackish water is discharged to keep the system clean (*Nat. Commun.* 2019, DOI: 10.1038/s41467-019-10817-6).

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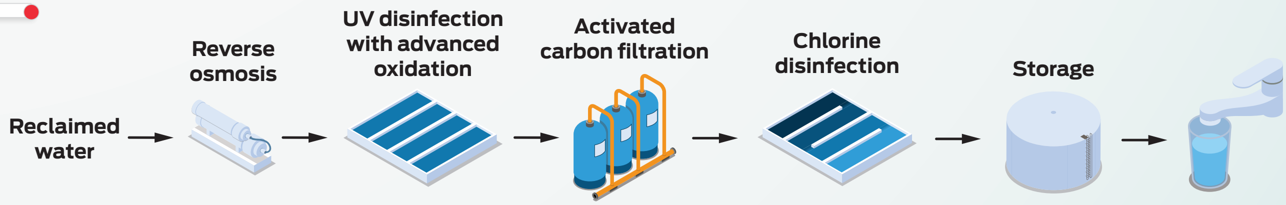


We choose 20 promising companies cleaning up water

374WATER°

» 374Water
» 374water.com
» **Based:** Durham, North Carolina
» **Launched:** 2018
» **Funding to date:** Not disclosed
» **Publicly traded:** Yes, IPO 2021
» **Key partnerships:** Merrell Brothers
» **Strategy:** 374Water breaks down per- and polyfluoroalkyl substances (PFAS) and other contaminants with water above its critical point of 374 °C and at about 220 times atmospheric pressure. Supercritical water acts like a cross between a liquid and a gas. In the presence of oxygen, it oxidizes organic compounds in waste and sludge into carbon dioxide, while producing clean water and energy that can be reused.
» **Why watch:** 374Water has sold units that can handle 6 metric tons (t) of waste daily to utilities in California and Israel.

Aclarity

» Aclarity
» aclaritywater.com
» **Based:** Hadley, Massachusetts
» **Launched: 2017**
» **Funding to date: $4.6 million**
» **Publicly traded: No**
» **Key partnerships:** Not disclosed
» **Strategy:** Aclarity's electrochemical water treatment system generates strong oxidants like hydroxyl radicals, chlorine, and ozone when water passes through its reactor. The oxidants destroy PFAS, other organic contaminants, and microbes. Dissolved metals precipitate as solids that can be filtered.
» **Why watch:** In 2021, Aclarity installed its first commercial-scale system for an undisclosed client that stores road salt.

aquafortus

» Aquafortus
» aquafortus.com
» **Based:** Mangere, New Zealand
» **Launched:** 2016
» **Funding to date:** Not disclosed
» **Publicly traded:** No
» **Key partnerships:** Rodi Systems
» **Strategy:** Aquafortus converts high-salinity wastewater to dry salt and clean water. The company's absorbent binds to water, leaving salts to crystallize from solution. Applying a regenerant releases the absorbent, and a membrane separates the regenerant and absorbent from the clean water.
» **Why watch:** Aquafortus tested its technology on brine from oil fields and recovered nearly all the water for reuse.

Aquagga

» Aquagga
» aquagga.com
» **Based:** Tacoma, Washington
» **Launched:** 2019
» **Funding to date:** $2.5 million
» **Publicly traded:** No
» **Key partnerships:** Emerging Compounds Treatment Technologies
» **Strategy:** Aquagga destroys PFAS compounds with hot, compressed—but not quite supercritical—water combined with a strong base. The company's hydrothermal alkaline treatment breaks the carbon-fluorine bonds in PFAS to yield clean water and safe salts.
» **Why watch:** In 2020, Aquagga took first prize in the US Environmental Protection Agency's Innovative Ways to Destroy PFAS Challenge as well as the Alaska Airlines Environmental Innovation Competition.

aquammodate

» Aquammodate
» aquammodate.com
» **Based:** Göteborg, Sweden
» **Launched: 2019**
» **Funding to date:** $894,000
» **Publicly traded:** No
» **Key partnerships:** Philos Membrane
» **Strategy:** Aquammodate purifies water by studding reverse osmosis membranes with aquaporin proteins, which conduct water through cell membranes but prevent other molecules from passing through. The firm keeps the proteins stable outside their natural environment by surrounding them with a layer of lipids and a silica shell, a strategy borrowed from single-celled microalgae called diatoms.
» **Why watch:** Aquammodate has partnered with membrane manufacturing company Philos to scale production of its biomimetic membranes.

AquaPao

» AquaPao
» aquapao.com
» **Based:** Princeton, New Jersey
» **Launched:** 2021
» **Funding to date:** $331,000
» **Publicly traded:** No
» **Key partnerships:** Not disclosed
» **Strategy:** AquaPao is developing membranes that use sunlight as a power source for off-grid water purification (see page 5). The technology is a hydrogel with a polymer coating designed to exclude pollutants like lead or nitrates. The layered material absorbs water like a sponge. Upon heating, it reversibly changes structure to release clean water.
» **Why watch:** AquaPao board member Justine Lee led Lyft's acquisition of bikeshare company Citi Bike.

cyclopure

» **Cyclopure**
» **cyclopure.com**
» **Based:** Skokie, Illinois
» **Launched:** 2016
» **Funding to date:** $22 million
» **Publicly traded:** No
» **Key partnerships:** Aecom, Tetra Tech, Waterkeeper Alliance, Witteveen+Bos
» **Strategy:** One of C&EN's 2019 10 Start-Ups to Watch, Cyclopure has devised an adsorbent with high selectivity for PFAS. The adsorbent's cup-shaped β-cyclodextrin molecules, derived from corn starch, connect to one another with rigid aromatic linker molecules. The resulting network of tiny cups catches PFAS and can be regenerated for multiple cycles. A mechanochemical process destroys the PFAS for safe disposal.
» **Why watch:** Cyclopure sells two products to consumers: home filters that are compatible with Brita countertop pitchers and a PFAS test kit for water. Nine pilot campaigns for municipal and industrial wastewater treatment are underway in multiple US states and at Travis Air Force Base.

ECOSTP®
sewage to gold™

» **EcoSTP Technologies**
» **ecostp.com**
» **Based:** Malleswaram, India
» **Launched:** 2017
» **Funding to date:** $260,000
» **Publicly traded:** No
» **Key partnerships:** Not disclosed
» **Strategy:** EcoSTP's underground water treatment plants are inspired by cows' multichambered stomachs and have no moving parts. Gravity moves water through progressive chambers that allow solid waste to sink. Bacteria from cow dung that don't require oxygen break down pollutants in the sewage. A final pass through wetland-inspired chambers enables plant roots to soak up more contaminants. With additional processing, the resulting water is usable for drinking.
» **Why watch:** EcoSTP has built 50 plants across India, and the company has plans to expand to Africa.

EcoWorth Tech

» **EcoWorth Tech**
» **ecoworth-tech.com**
» **Based:** Singapore
» **Launched:** 2016
» **Funding to date:** $740,000
» **Publicly traded:** No
» **Key partnerships:** Not disclosed
» **Strategy:** EcoWorth Tech's carbon fiber aerogel removes liquid organic contaminants like biofuels and fats from wastewater. The material can be made from cellulose-containing feedstocks such as cotton or waste paper. The aerogel holds up to 190 times its weight and can be squeezed to recover absorbed organic material and can be reused.
» **Why watch:** EcoWorth Tech was selected as one of the companies in the 2022 cohort at MassChallenge Switzerland, a global start-up accelerator.

evove

» **Evove**
» **evove.tech**
» **Based:** Sedgefield, England
» **Launched: 2015**
» **Funding to date: $2.7 million**
» **Publicly traded:** No
» **Key partnerships:** Hartree Centre, Hydrasyst
» **Strategy:** Evove overcomes biofouling and other problems that plague conventional membranes for water purification by applying a graphene oxide coating and a variety of 3D-printed spacer and insert technologies.
» **Why watch:** In December 2021, Evove launched a line of membranes with uniform pore size and distribution that can be customized for different applications.

FORWARD
WATER TECHNOLOGIES

» **Forward Water Technologies**
» **forwardwater.com**
» **Based:** Toronto
» **Launched:** 2012
» **Funding to date:** $2 million
» **Publicly traded:** Yes, IPO 2021
» **Key partnerships:** Aquaporin
» **Strategy:** Forward Water uses forward osmosis to purify water. In forward osmosis, a solution that's high in salt concentration extracts water from waste by drawing the water across a semipermeable membrane. The company's draw solution contains a switchable compound that can be phased to a gas. When the gas bubbles out of solution, clean water is left behind. The gas can be captured in a separate chamber and reused.
» **Why watch:** Forward Water conducted a pilot project with a waste and wastewater handler in Calgary, Alberta, to clean waste streams from the oil and gas industry.

I-PHYC
HARNESSING THE NATURAL POWER OF ALGAE

» **Industrial Phycology**
» **i-phyc.com**
» **Based:** Birmingham, England
» **Launched:** 2012
» **Funding to date:** $5.9 million
» **Publicly traded:** No
» **Key partnerships:** Essex and Suffolk Water, GENeco, Stirling Dynamics
» **Strategy:** Industrial Phycology harnesses algae to reduce phosphorus- and nitrogen-containing compounds in wastewater. Inside bioreactors, light-emitting diode lamps encourage photosynthesis in the company's specially conditioned microalgae, which rapidly take up the pollutants as nutrients. The algae are then recycled.
» **Why watch:** Industrial Phycology's latest funding round was the first to be led by the Mellby Gård AB Water Fund, a Swedish fund that invests in water technologies.

NALA
MEMBRANES

» **Nala Membranes**
» **nalamembranes.com**
» **Based:** Morrisville, North Carolina
» **Launched:** 2018
» **Funding to date:** $3.7 million
» **Publicly traded:** No
» **Key partnerships:** National Alliance for Water Innovation, Separation Technologies Applied Research and Translation Center, Singapore Membrane Consortium
» **Strategy:** Nala Membranes is developing precisely sulfonated, chlorine-tolerant polymer membranes for reverse osmosis water purification. Chlorine-containing disinfectants damage conventional polyamide-based membranes, making them

vulnerable to clogging from biological growth.
» **Why watch:** In November 2022, Nala Membranes won the Cleantech Research Innovation Award from the nonprofit Research Triangle Cleantech Cluster.

» **Nanoseen**
» nanoseen.com
» **Based:** Sopot, Poland
» **Launched:** 2020
» **Funding to date:** $450,000
» **Publicly traded:** No
» **Key partnerships:** Not disclosed
» **Strategy:** Nanoseen uses cheap, carbon-based filter elements to produce membranes with precisely controlled pore sizes. By stacking a series of nanomembranes with different pore sizes, the company can purify and desalinate water without an energy supply, using only gravity.
» **Why watch:** Nanoseen has a powder in development that aims to destroy microplastic and nanoplastic water pollution with photodegradation.

» **Onvector**
» onvector.us
» **Based:** Somerville, Massachusetts
» **Launched:** 2014
» **Funding to date:** $2.4 million
» **Publicly traded:** No
» **Key partnerships:** Not disclosed
» **Strategy:** Onvector's reactors generate ionized gas—plasma—to destroy wastewater pollutants such as PFAS. The reactor creates a controlled cyclone of water to maximize the water's exposure to the plasma. The company says its process is 97% more energy efficient than incinerating wastewater pollutants.
» **Why watch:** Onvector is pilot testing its technology on US Air Force bases, which used PFAS-containing firefighting foam for decades. The Department of Defense has mandated that such foams be phased out by 2024.

Note: Companies were included because of the novelty and potential of their methods, amount of capital raised, number of partnerships, and number and identity of investors.

Sources: Crunchbase (accessed October 2022), company websites, news reports.

» **Oxyle**
» oxyle.ch
» **Based:** Zurich
» **Launched:** 2020
» **Funding to date:** $3.6 million
» **Publicly traded:** No
» **Key partnerships:** Not disclosed
» **Strategy:** Oxyle designs nanoporous catalysts for wastewater treatment. In the presence of light or mechanical vibration, fleeting positive and negative charges develop on the catalyst's surface. These charges convert water to reactive oxygen species that break up pollutants.
» **Why watch:** Oxyle participated in Venturelab's Academia Industry Training Camp India in 2021. The program facilitates connections for companies interested in entering the Indian market.

» **Polykala Technologies**
» polykalatech.com
» **Based:** San Antonio, Texas
» **Launched:** 2018
» **Funding to date:** $393,000
» **Publicly traded:** No
» **Key partnerships:** Colorado School of Mines
» **Strategy:** Polykala Technologies creates polymer mats that remove PFAS from water. The product comprises an electrospun network of polyimide nanofibers coated with an organic material that binds PFAS selectively.
» **Why watch:** Polykala has created a prototype device for under-sink PFAS removal and is preparing to produce 1,000 units for household use.

» **Puraffinity**
» puraffinity.com
» **Based:** London
» **Launched:** 2015
» **Funding to date:** $7.4 million
» **Publicly traded:** No
» **Key partnerships:** Royal Academy of Engineering Enterprise Hub
» **Strategy:** Puraffinity offers adsorbent materials selective for PFAS. The company modifies substrates with molecular motifs that capture PFAS compounds, and it says that the motifs can be easily tweaked to capture the ever-expanding range of PFAS substances.
» **Why watch:** Puraffinity's advisers include experts who led developments in water technology for Dow.

» **Source**
» source.co
» **Based:** Scottsdale, Arizona
» **Launched:** 2014
» **Funding to date:** $270 million
» **Publicly traded:** No
» **Key partnerships:** Navajo Power, Patagonia
» **Strategy:** Source offers a technology that makes, stores, and dispenses clean drinking water pulled from the air. Solar-powered fans draw air into the device, where a desiccant engineered at the nanoscale absorbs water molecules. Heat captured by the device's solar panels triggers release of the water. The humidity inside the device becomes so high that the vapor condenses without needing to be chilled.
» **Why watch:** As of March 2022, Source's hydropanels were installed in 52 countries in 450 separate projects. Backers include Bill Gates's Breakthrough Energy Ventures.

» **ZwitterCo**
» zwitterco.com
» **Based:** Woburn, Massachusetts
» **Launched:** 2018
» **Funding to date:** $40.3 million
» **Publicly traded:** No
» **Key partnerships:** Digested Organics
» **Strategy:** One of C&EN's 2022 10 Start-Ups to Watch, ZwitterCo circumvents the clogs of proteins, fats, and oils that foul traditional water purification membranes. The company links zwitterions—molecules that have both positive and negative groups in proximity—with a polymer, creating precise channels for water while repelling molecules that cause clogs.
» **Why watch:** ZwitterCo's September 2022 series A funding, at $33 million, was one of the largest for a water company.

Jessica Ray: Materials for real-world water treatment

KATHERINE BOURZAC, C&EN STAFF

Jessica Ray is an environmental engineer whose practical solutions are built on some serious chemistry. "I want to make reactive materials and processes more useful for treating real water in the real world," she says.

Ray says we need to get as much value as possible out of the precious water we have—contaminated though it may be. "Stormwater runoff is often viewed as a nuisance," she says, but in fact it is a resource. One of her projects is aimed at turning a very Seattle sort of waste, used coffee grounds from the University of Washington, into biochar for rain gardens that can treat stormwater runoff. A priority in this effort is to keep chemicals from car tires out of the region's creeks, where they can interrupt salmon spawning. Ray and the university have filed an international patent application on this technology.

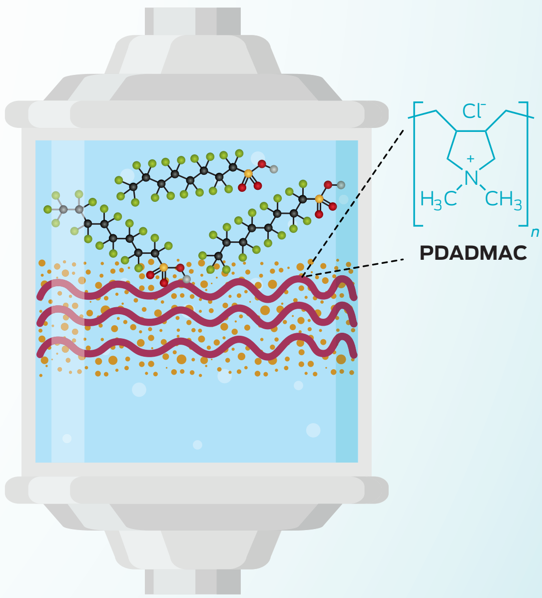
Ray is also turning her expertise to one of the biggest problems in environmental chemistry: how to get rid of persistent organic pollutants called per- and polyfluoroalkyl substances (PFAS). "PFAS can become lost in large-scale water treatment," she says. Granular activated carbon, the most common PFAS purifier, preferentially sops up more abundant organic contaminants, leaving behind trace but still potentially harmful levels of PFAS. Ray wants to "close the book on practical ways to manage PFAS," she says.

During her postdoc work, Ray developed a sand-like composite coated with polymers that target the carbon-fluorine PFAS backbone. The PFAS can then be selectively desorbed from the treatment medium, which allows Ray's team to concentrate the pollutant in order to more effectively break it down.

The usual PFAS abatement methods require stringent conditions, such as the absence of oxygen or high pH. Since starting her lab in 2019, Ray has been working on a simpler catalytic method for breaking down concentrated PFAS. It's based on a relatively young class of 2D electronic materials called MXenes, which have been explored primarily for use in energy storage. Their fast-charge kinetics and high surface area also make MXenes promising electrocatalysts for oxidizing PFAS, Ray says. In 2022, she received a National Science Foundation Faculty Early Career Development Program (CAREER) Award to support the MXene work.

Research at a glance

Ray is working on materials that remove environmental contaminants that are tough for water treatment systems to capture. Using clay particles (tan) mixed with poly (diallyldimethylammonium) chloride (PDADMAC) (red squiggles), she made a material that can adsorb organic contaminants, including the PFAS perfluorooctanesulfonic acid (ball-and-stick structures).



c&en's STEREO CHEMISTRY

Hear more from Dr. Ray

On C&EN's podcast, *Stereo Chemistry*, environmental engineers Jessica Ray and William Tarpeh explain how they use chemical engineering know-how to develop simple systems for filtering toxic chemicals from our water and harvesting useful chemicals from urine. Listen at **cenm.ag/discover-ray-tarpeh**

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CREDIT: UNIVERSITY OF WASHINGTON (RAY); YANG H. KU/C&EN/SHUTTERSTOCK (RESEARCH AT A GLANCE)

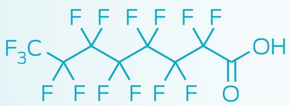
Simple chemical method destroys 2 classes of PFAS

KRYSTAL VASQUEZ, C&EN EDITORIAL FELLOW

Per- and polyfluoroalkyl substances (PFAS) have quickly become ubiquitous in the environment. These potentially toxic compounds are now being found in soil, groundwater, and even rain and snow. And they're expected to stay in the environment for years—perhaps centuries—as their sturdy fluorine-carbon bonds make it nearly impossible for them to degrade naturally. But scientists have now developed a way to permanently break down two classes of these so-called forever chemicals using relatively low temperatures and a few common reagents (*Science* 2022, DOI: 10.1126/science.abm8868). Brittany Trang, who co-led the study, presented the work at the ACS Fall 2022 meeting.

For years, researchers have been trying to find ways to remove PFAS from the environment—especially from drinking water. Current methods typically filter the compounds from water with activated carbon, which eventually needs to be incinerated at 1,000 °C to remove and destroy these pollutants.

This process is extremely energy intensive, however, and may not be as effective as previously thought, explained Trang, a science reporting fellow at the health-focused news outlet Stat who developed the method as a graduate student in William Dichtel's lab in the chemistry department at Northwestern University. Many emerging degradation methods for PFAS also require significant energy or chemical inputs, according to Dichtel, which could limit their use.

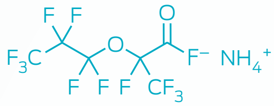


PFOA

In contrast, Trang and Dichtel's method can degrade one of the largest classes of PFAS, perfluoroalkyl carboxylic acids (PFCAs), using two inexpensive chemicals, ambient pressures, and mild temperatures of around 120 °C. Trang and her colleagues demonstrated that this process could also break down the ammonium salt of hexafluoropropylene dimer acid (HFPO-DA), a widespread PFAS pollutant colloquially known as GenX.

To accomplish these results, the researchers used heated dimethyl sulfoxide solvent to remove the carboxylic acid group from the ends of GenX and eight different PFCAs, including perfluorooctanoic acid (PFOA). This action left behind a highly reactive anion that readily fell apart when Trang added sodium hydroxide to the mix. All that remained in the end was a mixture of relatively benign fluoride ions and carbon-containing compounds. Northwestern is filing an international patent application on the technology. Dichtel says that while further commercial development remains an open question, he is interested in both start-up and licensing options.

This method has the potential to be "a cost-effective and efficient method" for treating concentrated PFCA and GenX waste streams, said Michael J. Bentel, a postdoctoral researcher at Clemson University who was not involved in the study. The study's value also lies in the researchers' explanation of how these PFCAs are being broken down, said Jinyong Liu, a University of California, Riverside, environmental engineer who was also not involved in the work.



HFPO-DA ammonium salt

After establishing that their method worked, Trang and her team determined that the fluorinated compounds degrade through a chemistry that differs from what others in the field had generally assumed. "The mechanism is supernovel," Liu said, and "can transform our understanding on how the perfluoroalkyl carboxylic acids degrade."

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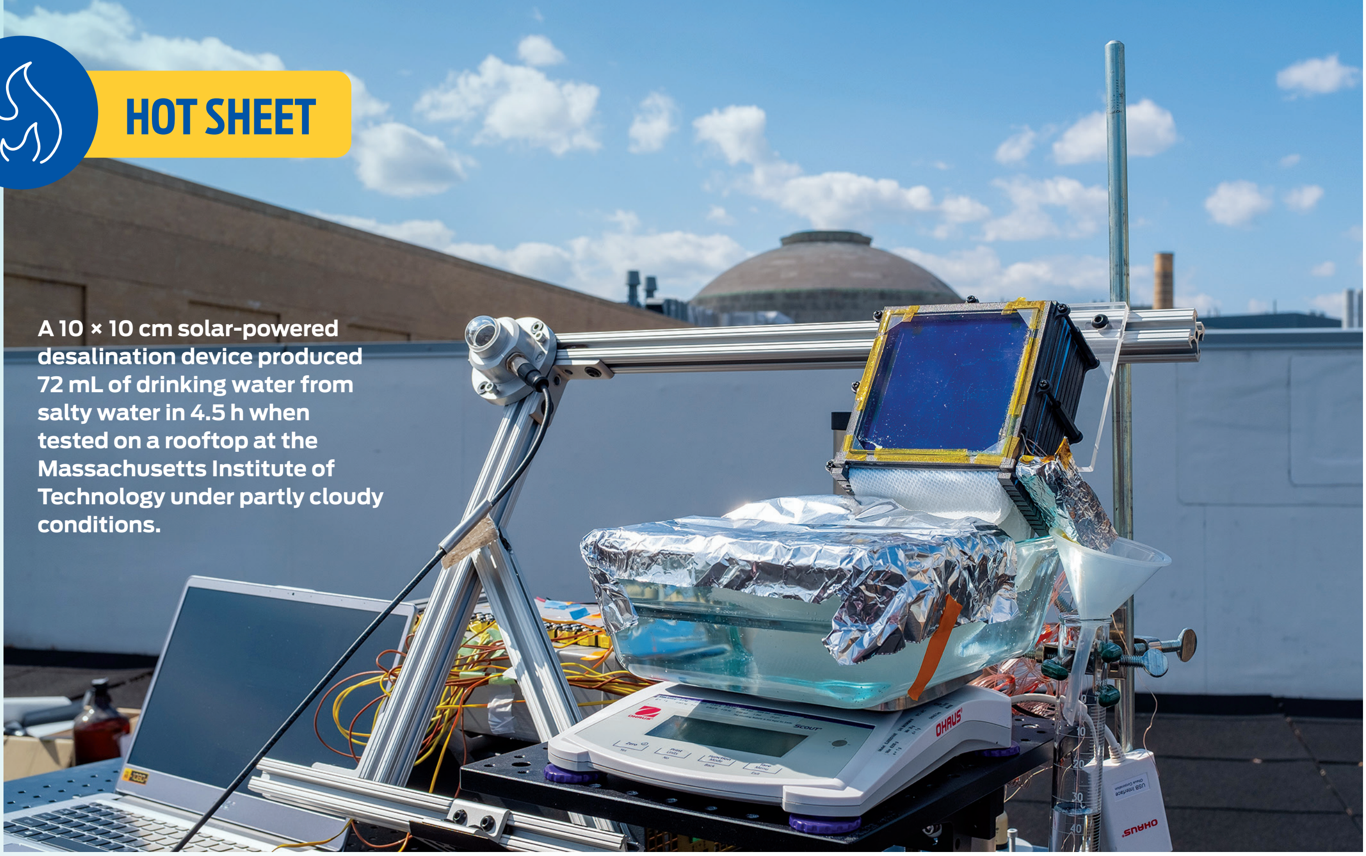
HOT SHEET



A 10 × 10 cm solar-powered desalination device produced 72 mL of drinking water from salty water in 4.5 h when tested on a rooftop at the Massachusetts Institute of Technology under partly cloudy conditions.

Superefficient solar desalination

PRACHI PATEL, SPECIAL TO C&EN

Portable devices that use sunlight to remove salts from seawater could provide affordable drinking water to people in remote or arid coastal areas. But solar-powered desalination technologies have suffered from low efficiencies. Researchers have designed an ultraefficient prototype that makes about a third of a cup of desalinated water in an afternoon and in ideal lab conditions makes almost three times as much as previous similar devices (*Energy Environ. Sci.* 2020, DOI: 10.1039/C9EE04122B).

Conventional desalination plants, which rely on membranes, are expensive and typically use a lot of energy. Solar thermal desalination is a less expensive option but is inefficient and requires immense parabolic mirrors to focus sunlight on seawater to evaporate it. Neither technology is suited for remote or resource-poor areas. Portable solar-powered desalination devices address this problem. They typically use less expensive, sunlight-absorbing materials that heat and evaporate seawater. The vapors are collected on a condenser, which gathers the desalinated water. The best systems can convert over 90% of the sun's energy to generate water vapor.

Evelyn Wang of the Massachusetts Institute of Technology, Ruzhu Wang of Shanghai Jiao Tong University, and their colleagues have now made a multistage system that goes way beyond this rate, boasting 385% efficiency when tested under ideal conditions. It does so by reusing the heat released when water vapor condenses and it is the first system to take advantage of this otherwise wasted energy.

This is a highly efficient and cost-effective approach to solar desalination, says Hadi Ghasemi, a mechanical engineer at the University of Houston not involved in the study. "This work brings the concept of solar heat localization a step closer to large-scale implementation."

The device contains 10 identical 3D-printed nylon frames stacked and placed on top of a water reservoir. Each frame has a paper towel that acts as the evaporator and an aluminum film that serves as the condenser. On the sun-facing side of the stack, the researchers place a black solar absorber. As the absorber heats up, it evaporates the water that the paper towel wicks up. As vapors condense on the aluminum film, the heat released gets channeled to the second paper towel, with the process repeating down the stack. Such a multistage approach has been used in major solar thermal desalination plants, says Lenan Zhang, one of Evelyn Wang's graduate students. "We transferred this idea into a portable design."

Based on laboratory tests of the 10 × 10 cm device, the researchers calculated that a meter-square device would produce 5.8 L of water per hour. In less-than-ideal conditions, on an MIT rooftop in summer, the device's performance was lower because of occasional clouds and wind. On the roof, the device produced 72 mL of water in 4.5 h, for a

“This work brings the concept of solar heat localization a step closer to large-scale implementation.”

calculated average of 2.6 L/m^2 per hour. To meet the average daily water needs for an adult or a small family, you could create an array of the multistage devices, Zhang says.

The researchers have since tested the device in Shanghai, which is about two-thirds as sunny on average as the Boston area. “Our design can work well in multiple different locations,” Zhang says. He adds that several companies have contacted the team, which is trying to better understand potential markets and determine the best route to commercialization.

The prototype costs about $1.50, or $15/$m^2$ for each stage in the 10-layer stack. But the 3D-printed nylon frame accounts for 70% of that, Zhang says, so there’s room for improvement. The group’s most recent calculations show that to be price competitive with tap water, a solar desalination device would have to produce over 5 L/m^2 of water per hour, cost less than $100/$m^2$, and last for at least 7 or 8 years (*Energy Environ. Sci.* 2021, DOI: 10.1039/D0EE03991H). “That is highly economically favorable to the real-world market demand,” Zhang says.

In February 2022 the team reported a new design that both reduces cost of materials and lengthens performance lifetime. Salt accumulation in the paper towel or any other wicking material reduces efficiency over time, Zhang says. So he and his colleagues designed a new, wick-free system (*Nat. Commun.* 2022, DOI: 10.1038/s41467-022-28457-8).

They placed a dark solar absorber layer atop a thin layer of water on a layer of polyurethane foam perforated with 2.5 mm channels. Under the perforated material is a deep reservoir of salty water. The system relies on a natural convective circulation between the warmer, thin layer of water above and the colder reservoir below. At the water surface, the sun’s heat produces desalinated water vapor. As this occurs, the very top layer of water becomes more salty and dense, which makes it flow down through the pores into the bulk water, leading to a passive liquid flow.

This preliminary device does not reuse heat, but its 80–90% efficiency is comparable to the best solar desalination systems of its type. And because it doesn’t require 3D-printed material, its cost for components can be low—just $4/$m^2$, Zhang estimates.

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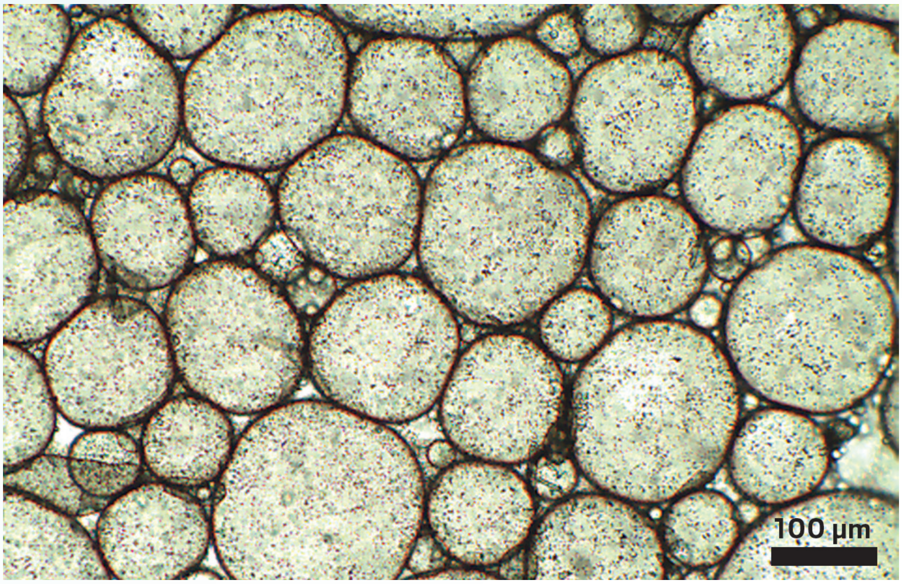
HOT SHEET

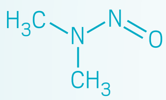
Chemistry in Pictures: MOF emulsion



CREDIT: ZHIWEI WANG, SHIHONG LIN, *SCI. ADV.* 2022, 10.1126/SCIADV.ABM4149

CRAIG BETTENHAUSEN,
C&EN STAFF

Reverse osmosis is used worldwide to purify drinking water. It is deployed at extremely large scale in desalination plants and is a leading technology in potable water reuse, also called toilet to tap—a nickname that annoys scientists and engineers working on potable water reuse. Though existing reverse osmosis membranes remove salt and most contaminants, a few slip through. They include boron and *N*-nitrosodimethylamine (NDMA, shown), a toxic by-product of the chlorination used upstream to kill pathogens. A team from China's State Key Laboratory of Pollution Control and Resource Reuse, the University of Hong Kong, and Vanderbilt University used nanoflakes of an amphiphilic metal-organic framework (MOF) to create a next-generation polyamide membrane. The MOF flakes line up on the interface between the water and hexane emulsion. Amide polymerization takes place at the interface, and the MOF regulates the heat and mass transfer associated with the reaction. This microscope image shows the result of the researchers' whipping the mixture into an emulsion to probe how the MOFs behave at the interface. The final result is a thin, crumpled membrane material that outperforms conventional membranes in removing salt, boron, and NDMA (*Sci. Adv.* 2022, DOI: 10.1126/sciadv.abm4149).



***N*-Nitrosodimethylamine (NDMA)**

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Our picks of the patent and journal literature on clean water

2022

» Crider, Yoshika S., Sanjeena Sainju, Rubika Shrestha, Guillaume Clair-Caliot, Ariane Schertenleib, Bal Mukunda Kunwar, Madan R. Bhatta, Sara J. Marks, and Isha Ray. **"Evaluation of System-Level, Passive Chlorination in Gravity-Fed Piped Water Systems in Rural Nepal."** *Environ. Sci. Technol.* (Sept. 20, 2022). DOI: 10.1021/acs.est.2c03133.

» Battelle Memorial Institute. **"Salt Separation and Destruction of PFAS Utilizing Reverse Osmosis and Salt Separation."** US Patent 11,407,666, filed Aug. 6, 2021, and issued Aug. 9, 2022.

» Nieuwendaal, Ryan C., Jeffrey D. Wilbur, Dean Welsh, Velencia Witherspoon, and Christopher M.Stafford. **"A Method to Quantify Composition, Purity, and Cross-Link Density of the Active Polyamide Layer in Reverse Osmosis Composite Membranes Using ^{13}C cross polarization magic angle spinning nuclear magnetic resonance spectroscopy."** *J. Membr. Sci.* (Feb. 5, 2022). DOI: 10.1016/j.memsci.2022.120346.

2021

» Aquacycl. **"Scalable Floating Micro-Aeration Unit, Devices and Methods."** US Patent 11,186,503, filed Feb. 27, 2020, and issued Nov. 30, 2021.

» Cyclopure. **"Charge-Bearing Cyclodextrin Polymeric Materials and Methods of Making and Using Same."** US Patent 11,155,646, filed Feb. 12, 2021, and issued Oct. 26, 2021.

» Aquafortus Technologies. **"Thermo-Responsive Solution, and Method of Use Therefor."** US Patent 11,020,706, filed Oct. 4, 2017, and issued June 1, 2021.

» Cherukumilli, Katya, Max Steiner, and Jessica R. Ray. **"Effective Fluoride Removal Using Granular Bauxite Filter Media as an Affordable and Sustainable Alternative to Activated Alumina."** *Environ. Sci.: Water Res. Technol.* (May 14, 2021). DOI: 10.1039/D1EW00033K.

» Xu, Xiaohui, Sehmus Ozden, Navid Bizmark, Craig B. Arnold, Sujit S. Datta, and Rodney D. Priestley. **"A Bioinspired Elastic Hydrogel for Solar-Driven Water Purification."** *Adv. Mater.* (March 31, 2021). DOI: 10.1002/adma.202007833.

» NASA. **"Supercritical Water Oxidation Flame-Piloted Vortex Flow Reactor."** US Patent 10,954,152, filed March 4, 2020, and issued March 23, 2021.

» Onvector. **"Microbubble Generator for Enhanced Plasma Treatment of Liquid."** US Patent 10,941,062, filed Nov. 15, 2018, and issued March 9, 2021.

» Culp, Tyler E., Biswajit Khara, Kaitlyn P. Brickey, Michael Geitner, Tawanda J. Zimudzi, Jeffrey D. Wilbur, Steven D. Jons, et al. **"Nanoscale Control of Internal Inhomogeneity Enhances Water Transport in Desalination Membranes."** *Science* (Jan. 1, 2021). DOI: 10.1126/science.abb8518.

2020

» Ganiyu, Soliu Oladejo, Carlos A. Martínez-Huitle, and Mehmet A. Oturan. **"Electrochemical Advanced Oxidation Processes for Wastewater Treatment: Advances in Formation and Detection of Reactive Species and Mechanisms."** *Curr. Opin. Electrochem.* (Dec. 31, 2020). DOI: 10.1016/j.coelec.2020.100678.

» Industrial Phycology. **"Photobioreactor."** US Patent 10,829,398, filed Dec. 5, 2013, and issued Nov. 10, 2020.

» Kurita Water Industries. **"Reverse Osmosis Treatment Method and System."** Japan Patent 2020/008884, filed June 19, 2019, and issued Oct. 28, 2020.

» Zhao, Jianwei, Jing Zhang, Dalei Zhang, Zhanbo Hu, and Yingjie Sun. **"Effect of Emerging Pollutant Fluoxetine on the Excess Sludge Anaerobic Digestion."** *Sci. Total Environ.* (Aug. 24, 2020). DOI: 10.1016/j.scitotenv.2020.141932.

» Zhao, Yuanyuan, Xiaobin Yang, Linlin Yan, Yongping Bai, Songwei Li, Pavel Sorokin, and Lu Shao. **"Biomimetic Nanoparticle-Engineered Superwettable Membranes for Efficient Oil/Water Separation."** *J. Membr. Sci.* (Aug. 20, 2020). DOI: 10.1016/j.memsci.2020.118525.

» The University of California and the Massachusetts Institute of Technology. **"Sorption-Based Atmospheric Water Harvesting Device."** US Patent 10,683,644, filed April 5, 2019, and issued June 16, 2020.

» Srimuk, Pattarachai. Xiao Su, Jeyong Yoon, Doron Aurbach, and Volker Presser. **"Charge-Transfer Materials for Electrochemical Water Desalination, Ion Separation and the Recovery of Elements."** *Nat. Rev. Mater.* (April 22, 2020). DOI: 10.1038/s41578-020-0193-1.

Note: This list was chosen by experts who work in the field, CAS information scientists, and C&EN editorial staff.